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Numerical assessment of the impact of roof reflectivity and building envelope thermal transmittance on the UHI effect

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Abstract

Cool materials benefits for the mitigation of the urban microclimate overheating caused by Urban Heat Island (UHI) effect are well-established at international level. Since the need for building energy efficiency is more and more pushing towards highly insulated envelope, there is a growing need for studies that address the correlation between the optical properties of building coatings and the thermal transmittance of the envelope where they are applied, also assessing their mutual impact on the UHI. The present paper reports a study, carried out through a fluid-dynamic microclimate simulation software in an Italian urban context, aiming at understanding the impact of the combination of several roof covering optical properties and building envelope U-value levels on the UHI, given the recent nation threshold values for both. The outcomes of the simulations, performed in urban contexts with a typical morphology of Italian town centres and under different climatic conditions, highlight how the increase of the environment air temperatures is influenced by the combinations of the following factors: lower urban canyons, roof surfaces with low solar reflectivity and highly insulated envelopes. In fact, the high insulation levels, in response to current regulatory standards for the reduction of winter energy consumption, inhibit the ingoing thermal fluxes (thermal decoupling phenomenon) leading to an increase of the external surface temperatures and consequently heating up the surrounding area. In this regard, the adoption of reflective materials can be beneficial in attenuating the overheating. Simulation results demonstrate that these materials are able to mitigate the outdoor air temperature until 2°C, depending on specific building envelope configurations and geographical locations.

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1. Introduction

Nowadays, about half of the population worldwide live in urban areas and this number is expected to grow in the forthcoming years. Consequently, Urban Heat Island (UHI) phenomenon, associated with a temperature discrepancy between warmer cities and cooler rural surroundings [1], is likely to become more and more impacting on the urban microclimate. Built surfaces that are mainly composed by materials with high solar absorbance and low solar reflectivity heavily contribute to the UHI, as well as the presence of green areas and the variable morphology of the urban canyons, characterized by a wide arrangement of buildings along the city streets.

It is possible to control the incident solar irradiance hitting the building external walls with the adoption of "cool" materials, primarily used for roof coatings, characterized by high values of solar reflectivity (commonly also called "albedo") and thermal emissivity, hence leading to a low surface temperature. Over the last decades, it was well established that at urban scale, a cool roof helps mitigating the surrounding urban outdoor overheating caused by UHI effects [2-4]. At building scale, a cool roof can reduce the amount of ingoing heat flow providing mean low indoor temperatures, consequently resulting in energy saving for cooling loads in summer, even if the effects on the overall annual performance is still arguable. Furthermore, cool roof benefits need to be further investigated considering recent trends towards highly insulated envelopes in construction sector [5].

In the Italian legislative framework, this matter has become more and more relevant in sustainability protocols (as LEED and ITACA [6,7]), and building energy efficiency legislation (DM 26.6.2015) [8]. These introduced threshold values with respect to envelope radiative properties and especially for the roof component, with the aim of reducing the UHI and the building cooling loads. In particular, DM 26.6.2015 requires to perform a cost-benefit assessment of the use of high-reflectance finishing materials (minimum solar reflectance values: 0.65 for flat roofs; 0.30 for pitched roofs). Although these limits are still not mandatory within the Italian legislation, they represent a benchmark for the roof design hence directly affecting the choice of building materials in the future.

The present paper reports the outcomes of numerical investigations carried out to assess the relationship among the radiative properties and the thermal transmittance of roofs, taking into account the threshold references in the Italian legislation, and their impact on the Urban Heat Island phenomenon in typical Italian climatic areas.

2. Urban Heat Island and building components

During summer days, roads and building surfaces exposed to the sun are prone to absorb a significant amount of the incident radiation, thus enhancing both the urban heat release and the outdoor discomfort. Moreover, high summertime temperatures in built areas increase energy demand for cooling. In this context, the roof is the component of the building envelope more exposed to the solar radiation. The outdoor heat wave impacts directly on its opaque surface, thus significantly incrementing its peak temperature that reaches higher values than the outdoor environment [9]. Consequently, heat can be absorbed and transferred to the building, also depending on the component U-value, contributing to summer indoor overheating and cooling consumption. Nahar et al. [10] reported that the thermal flow that comes from the roof is about 50% of the daily internal heat gains. Hence, the roof has a crucial role in the thermal and energy performance of a building as well as in the mitigation of the urban micro-climate.

In recent times, strategies for mitigating the effects of UHI represent a largely discussed issue in the scientific community. A significant UHI reduction strategy concerns the adoption of coating materials characterized by high solar reflectance, able to cool down the roof surface when hit by solar radiation with respect to traditional roof tiles, under the same boundary conditions [11].

The benefits of cool roofs are then well-established at international level. In Italy, a numerical study, carried out by Costanzo et al. [12] highlighted the positive contribution of high albedo strategies to cool down the outdoor environment. In the same climatic area, Zinzi et Agnoli [13] numerically demonstrated that the adoption of high albedo roof techniques coupled with existing buildings with low insulation level positively affects the urban heat island phenomenon, decreasing the outdoor surface temperature of about 2°C. Similar results were confirmed by Pisello et al. [14] through an experimental summer monitoring campaign, reporting a significant reduction of the outdoor peak temperatures by substituting a bituminous membrane with a performing cool paint.

Moreover, Sanjai et al. [15] classified cool roofs as a sustainable passive cooling strategy, therefore suitable for building heritage interventions in historical centres. Several numerical investigations are oriented today towards the architectural integration of cool roof systems, as testified by the introduction of cool clay tiles in traditional urban contexts, proven successful for the reduction of both cooling loads and the mitigation of the UHI effect [16-18].

However, rigorous predictions of buildings indoor/outdoor climate conditions at simulation stage need to assess additional boundary factors that affect the UHI phenomenon, as the urban high density morphology [19-20], the wind features [21-22], the presence of vegetation [23] and the smart use of shading devices [24]. Moreover, Costanzo et al. [25] propose a specific algorithm to correctly simulate the convective heat transfer coefficient between the roof surface and its surroundings.

Since the need for energy efficiency at European level is more and more pushing towards highly insulated buildings, there is a growing need for studies that address the correlation between the optical properties of the coatings and the thermal resistance of the envelope in which they are applied, also assessing their impact on both the UHI effect and the buildings cooling needs. According to some studies [5,26,27] the adoption of cool materials is beneficial in highly insulated roofs to mitigate the thermal decoupling between the indoor and outdoor environment phenomenon caused by the high insulation level. Moreover, Costanzo et a. [28] carried out several simulations in three different Italian locations underlining the overall positive effect of cool paints in highly insulated buildings in reducing the annual primary energy consumption. This outcome needs to be further investigated in the Italian context, considering the recent legislative framework evolution and the national very diversified climatic features.

3. Methodology

According to national reference values for the radiative properties of roof materials and the roof thermal transmittance, the assessment of the impact on the UHI of different roof covering materials (with several levels of optical properties representative of both standard tiles and cool materials), coupled with different roof U-values, was performed through ENVI-met [29], a software for urban microclimate simulations based on surface-plant-air interactions. Simulations were performed in three Italian urban contexts, in order to understand the impact of roof solar reflectivity and emissivity in different climate conditions, as described in the following sub-sections 3.1 and 3.2. The main outcomes of the evaluations are reported in section 4, while conclusions are drawn in section 5.

3.1. The micro climate urban modelling and simulation

Fig. 1. Areal view of the urban portion selected for the microclimate simulations and representation of the model through ENVI-met. On the right, the 30 points of simulation data collection are identified (in particular, point 20).

For this study, an urban context representative of a typical Italian town center morphology has been selected. The town portion is located in Rome, close to Piazza Navona, and is characterized by a high density urban pattern, typical of the most ancient areas of Italian towns (Fig. 1). It includes a range of urban canyon geometries, namely different ratios between the height of the buildings (h) and the distance (d) between them, leading to a h/d ratio among 1 and 5.3. Low h/d values represent urban canyons with a high level of sunshine, due to the presence of lowrise buildings with respect to the size of the roads. Inversely, very high values denote urban built surfaces characterized by poor solar radiation due to the presence of narrow streets, typical of the majority of Italian historical town patterns.

The urban portion has a square-shaped dimensions of 100x100 m (10000 m^2) and was meshed into a grid of 100x100x40 cells in three dimensions. The dimensions of the cells are 1x1x2 m, thus leading to some simplifications for the digital modeling of the buildings geometry.

The simulation process was carried out during one typical summer week, considering the solar radiation profiles included into ENVI-met database for three Italian locations (Turin, Rome, Palermo) belonging to very different climatic areas. This allowed to point out the influence on the outdoor air temperatures given by the specific geographic locations when the pattern of the urban canyon remains the same, moreover typical of all Italian historical centers. The meteorological framework set for the simulations also included: the wind speed (2.2 m/s, measured at 10m height, typical of Italian unventilated summer days), the wind direction (from West), the outdoor relative humidity (50%), the initial air temperature (22°C). The building internal temperature was set at 26°C.

For the urban streets areas, default unsealed soil properties were adopted (solar reflectance of 0.2 and thermal emissivity of 0.98), while the roughness length factor was set at 0.015. Generalizations referring to the geometric models of the buildings and their components were adopted, considering the urban scaling in which the simulations were conducted and the characteristics of the analytical models adopted, thus omitting detailed material layers for the building components and potential air motions between them. Moreover, additional inputs as vegetation and pollution levels do not fall within the sphere of this research.

The simulations were performed referring to an hourly timesteps and results focused on a single day featured by the highest outdoor temperatures. Furthermore, the interpretation of the outcomes is based on the interpolation of the data collected in 30 points (reported in Fig. 1) belonging to the aforementioned urban portion, disregarding fringe areas, greatly affected by the imposed boundary conditions. Results particularly focused on point 20 (highlighted in Fig. 1), representative of a town geometry characterized by a h/d ratio of 1.32. Each point is placed 1.8 m above ground level, as to ensure that the results are consistent with the perception of an average user.

3.2. The simulated roofs configurations

Several configurations were attributed to the buildings modelled in the urban environment, obtained by combining different roof covering optical properties and envelope's thermal transmittance levels. In detail, the following building features were combined:

- Five roof covering materials, which correspond to five solar reflectance-emissivity combinations, representative of the traditional Italian products and of new solutions facing the market (as cool materials);
- Three U-value levels for the building envelope, according to those of the typical existing buildings and those established by past and actual Italian legislation frameworks on building energy efficiency.

The simulated optical properties (solar reflectivity, absorbance and emissivity) of the roof external surface are reported in Table 1. The Z0 category represents a bitumen-coated or a very dark-colored roof (included as an "extreme" case). Z4 is representative of a cool materials, characterized by high values of reflectivity and emissivity. Z1-Z3 solutions represent the typical range for clay roof tiles in Italy. For Z3 case, we considered a thermal emissivity much lower than the typical value for clay tiles in order to assess the potential impact of this specific property on the results.

The different levels of the envelope U-value (external walls and roofs) are presented in Table 2, together with the standards required by Italian D.Lgs 311/2006 [30] –the past regulation- and by D.M. 26/06/2015 [8] – the actual one. In particular, D.M. 26/06/2015 does not impose compulsory envelope U-values for new buildings, but suggests threshold values for a "Reference Building" (those reported in table 2). That is a building with the same geometry, orientation, geographical location, destination of the building currently under design, with a specified global energy performance level.

Table 1. Radiative properties of the simulated roof coverings.

ID	Solar Reflectance (ρ)	Absorbance (α)	Emissivity (ε)
Z0	0.05	0.95	0.95
Z1	0.26	0.74	0.9
Z2	0.47	0.53	0.87
Z3	0.68	0.32	0.40
Z4	0.89	0.11	0.87

In details, "ST" represents the typical U-value levels of existing buildings envelopes. In particular, ST roof configuration includes a hollow-core structure with an aggregate concrete slab and a coating. "IS" features the envelope U-value levels established by past Italian legislation D.Lgs 311/2006 for buildings in climatic zone D (Rome). To obtain this U-value requirements, the roof is insulated by approximatively 9 cm of insulation (thermal conductivity 0.034). Finally, "IP" represents buildings characterized by high insulation levels (14 cm insulation) as required by the current legislation (D.M. 26/06/2015) for reference buildings in climatic zone E (Turin) starting from 2019 for public buildings (2021 for private ones). In this way IP features quite restrictive values for envelope insulation. Moreover, for existing buildings facades (ST) included into the urban areas, a solar reflectance value of 0.38 and a thermal emissivity value of 0.92 were selected, whereas for IP and IS configurations, the optical properties of the wall surfaces were 0.33 for the solar reflectance and 0.85 for the thermal emissivity.

The combination of the five roof radiative properties levels with the three buildings insulation levels resulted in 15 configurations that were simulated in the three different climatic contexts (Turin, Rome and Palermo).

Table 2. Thermal transmittance of the simulated building components and reference values in the Italian Legislation

Building component	ID	Simulated U-value [W/m²K]	U-value [W/m²K] *D.Lgs. 311/2006 (from 2010)*			U-value [W/m²K] *D.M. 26/07/2015 (from 2019 for public buildings)*		
			Climatic zone B (Palermo)	Climatic zone D (Rome)	Climatic zone E (Turin)	Climatic zone B (Palermo)	Climatic zone D (Rome)	Climatic zone E (Turin)
Roof	**ST**	**2.10**	0.38	**0.32**	0.30	0.35	0.26	**0,22**
	IS	**0.32**						
	IP	**0.22**						
External wall	**ST**	**1.39**	0.48	**0.36**	0.34	0.43	0.29	**0.26**
	IS	**0.36**						
	IP	**0.26**						

4. Results and Discussion

The daily outdoor mean air temperatures distribution in the 30 simulation points representative of different typologies of urban canyons, mainly characterized by existing buildings with poor insulation and clay tiles covering (intermediate solar reflectance levels, between Z1 and Z3) is presented in Fig. 2, in relation to the h/d ratio. It is not possible to establish a specific correlation law between the geometry of the urban context and the outdoor air temperature, but a typical trend can be drawn, namely the fact that the temperatures decrease with the increasing of the h/d ratio (until 2°C for this urban context). This is due to the fact that urban canyon characterized by high values of h/d are subjected to limited solar radiation. As expected, the adoption of clay tiles with lower reflectance values (Z1), for the same geometrical characteristics of the urban canyon, results in higher surrounding outdoor mean air temperatures (averagely of about 1°C).

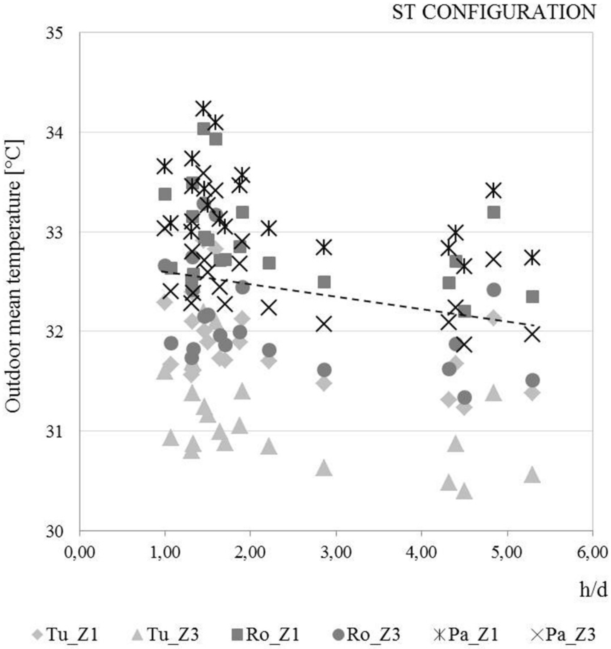

Fig. 2. Daily outdoor mean air temperatures distribution in the 30 simulation points in relation to the h/d ratio, for the buildings with the ST configuration (low insulation) and roofs solar reflectance values between Z1 and Z3.

In addition, Fig. 3 correlates the outdoor temperature distribution (now averaged in 24 hours, so including the night values), in the 30 points referred to the urban canyons of Turin, Rome and Palermo in relation to all the roof solar reflectivity levels, keeping constant the building insulation level (ST configuration). As expected, the mean temperature generally decreases by increasing the covering reflectivity and this trend is detectable in all the climatic areas. This is particularly true for the warmer area of Palermo, where the mean temperature difference among the extreme reflectivity is about 1°C, while in the colder Turin it is about 0.9°C.

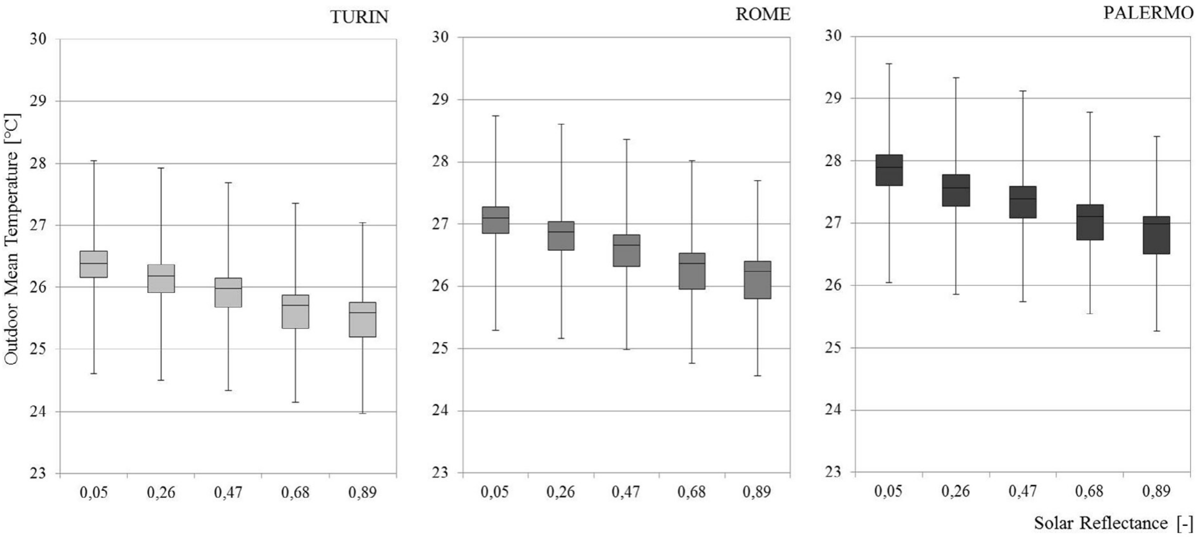

Fig. 3. Box whiskers plots of the outdoor daily mean temperatures in the 30 points referred to the urban canyons of Rome, Turin and Palermo, considering the building ST configuration and all the five levels of roof solar reflectivity.

Fig. 4 represents the outdoor air daily temperature trend detected on a specific point of the urban canyon (point 20) in the three geographical locations. Temperature profiles are represented for the roof configurations with extreme levels of covering reflectivity (Z0 and Z4) and envelope insulation (ST and IP). For existing buildings with poor insulation (ST) and low roof reflectivity (Z0), the outdoor air temperatures range from 37°C to 40°C. The adoption of cool materials allows to reduce the peaks, with a variation range from 35,5°C to 38,5°C.

Instead, for highly insulated constructions, surface temperatures are higher as a result of the thermal decoupling among the external layers of the envelope and the building indoor environment. In fact, they vary from 39°C to 42°C for Z0 configurations, whereas high albedo coatings lower this range (from 38°C to 41°C), thereby reaching similar values to those detected for the low insulation roof technology with low solar reflectance.

As expected, in the hottest city (Palermo), the outdoor air temperature reaches the highest values both for minimum and maximum insulation levels and the temperature drop between the adoption of a traditional system and a cool roof is around 1,6°C. Moreover, the temperature gradient slightly decreases as the climatic location switches towards colder climates (1.4°C in Rome and 1.3°C in Turin).

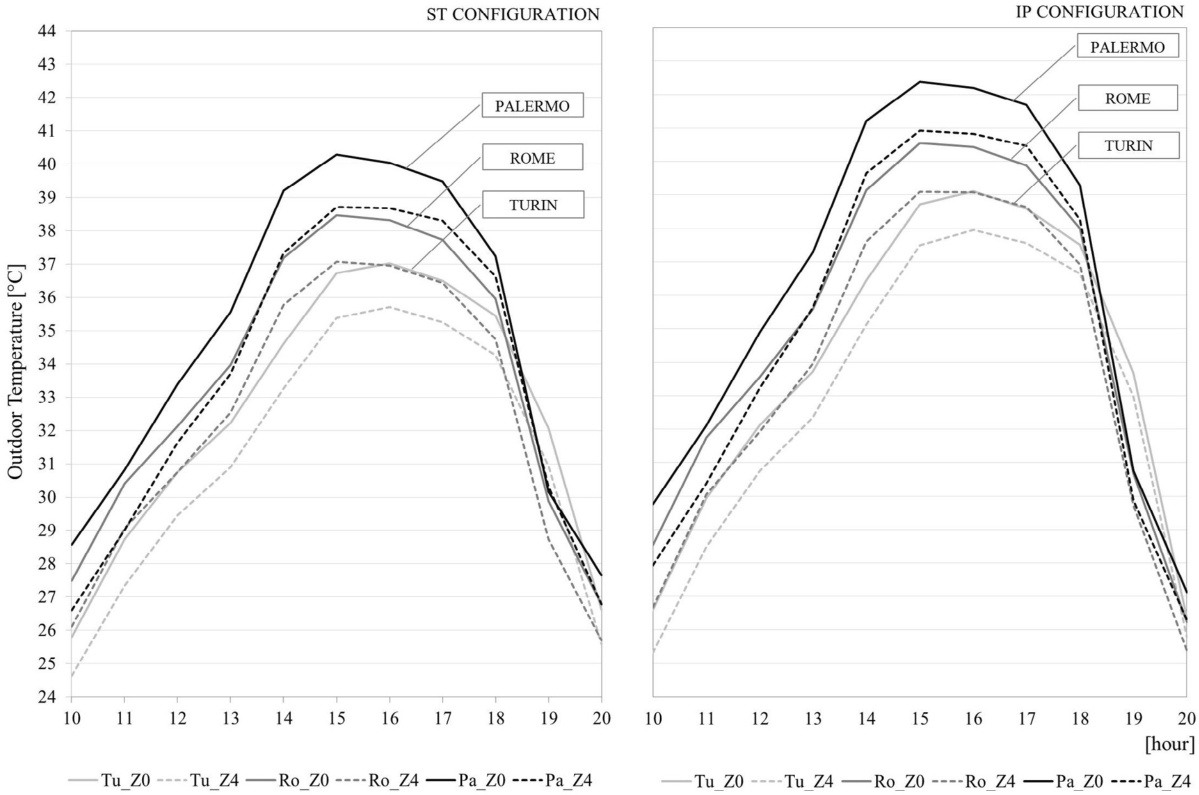

Fig. 4. Daily outdoor temperature trends of the urban canyon (Point 20) in the three geographical locations analysed, for the roof configurations with the extreme levels of covering reflectivity (Z0= minimum, Z4=maximum) and envelope insulation (ST and IP).

Finally, Fig. 5 summarizes the outdoor daily mean temperature profiles detected in Turin, Rome and Palermo, averaged for all the simulation points of the urban areas, for the roof configurations with the extreme levels of covering reflectivity (Z0 and Z4) and envelope insulation (ST and IP). The graph further confirms the results previously presented, even if the temperatures values are a bit lower due to the averaging in all points. The mean temperature values vary around 1,5-2°C, according to the reflectivity level and the city latitude, irrespective of the envelope insulation level.

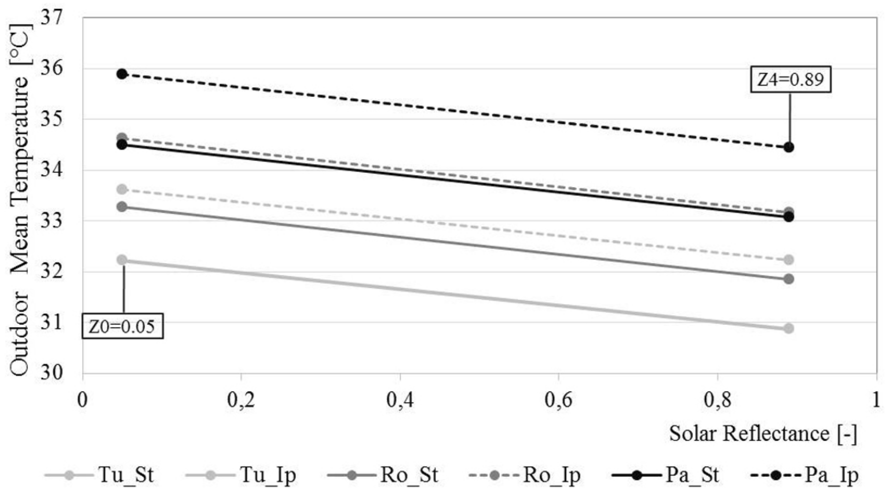

Fig. 5. Outdoor daily mean temperature trend in three geographical locations, averaged on the 30 simulation points, for two levels of thermal insulation (ST and IP) and two extreme values of solar reflectance (Z0 and Z4).

Furthermore, other than the rising of the outdoor air temperature peaks due to the adoption of roof materials characterized by low levels of solar reflectance, it is possible to point out the impact of the envelope thermal resistance. Highest air temperatures (with values fitting in a wide range from 32.2°C to 35.8°C) are obtained when simulations are performed for envelopes with lower thermal transmittance (IS and IP configurations achieve very similar results, so IS solutions are not reported in the graphs). Among them, low reflectance roof materials have the worst behavior (33.6°C in Turin, 34.6°C in Rome and till 35.8°C in Palermo), contributing to the increase of the outdoor air temperature, thus the UHI. This situation occurs in all the three weather locations, with respect to their latitude levels.

From the results obtained, it is clear that, if the thermal transmittance of an external surface is very low, the thermal decoupling that occurs between the building indoor and outdoor thermal conditions, due to the high insulation level, enhances the surface temperatures of the building components, slightly rising the surrounding outdoor air. Envelopes designed with high thermal resistance then impact more on the outdoor temperature, thus enhancing the urban heat island phenomena.

Therefore, the adoption of low values of solar reflectance significantly impacts on the outdoor air temperature. The difference between the maximum values of outdoor temperatures, considering different envelope configurations, is constant (about 1-2°C), in relation to the specific geographical location.

In addition, it should be noted that the reflectivity levels typical of traditional clay tiles (Z1-Z3) are already quite effective in reducing the temperatures achieved by Z0 configuration (which represents an "extreme" level).

5. Conclusions

The present paper reports a study, carried out through a fluid-dynamic simulation software in an Italian urban context, aiming at understanding the impact of the combination of several roof covering optical properties and building envelope thermal transmittance levels on the urban heat island phenomenon. In particular, the outdoor temperature trend has been assessed in a typical town morphology with a characteristic urban pattern, under three different climatic Italian conditions.

The effect of the adoption of envelopes with different U-values on the surrounding outdoor temperature has been evaluated, considering that the inhibition of the ingoing thermal fluxes due to the high insulation levels could lead to an increase of the outdoor surface temperatures and consequently heat up the surrounding area.

Results highlight how the increase of the outdoor mean air temperatures is influenced by the combinations of the following factors: lower urban canyons, roof surfaces with low solar reflectivity and highly insulated envelopes (enhancing the envelope thermal decoupling).

In this regard, the adoption of reflective materials can be beneficial in attenuating the overheating phenomenon occurring ever more in the highly insulated building envelopes in response to current regulatory standards for the reduction of winter energy consumption. Nonetheless, the impact of these strategies for the summer energy saving deserves to be further researched, also in terms of cost-benefit analysis.

In warmer Italian environments, could be more convenient investing less in the envelope's thermal insulation in favor of mild outdoor temperatures reached by traditional roof coverings such as clay tiles, naturally having satisfying radiative properties.

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