Effect of High-albedo Materials on Pedestrian Thermal Sensation in Urban Street Canyons in Hot Climates

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ABSTRACT: Extensive use of high-albedo materials has been advocated as a means of mitigating the urban heat island, especially in warm-climate cities. The implicit assumptions of this strategy are that by lowering canopy layer air temperature, cities will enjoy a) reduced air conditioning loads in buildings and b) improved thermal comfort for pedestrians in outdoor urban spaces. The second of these assumptions is examined here by means of computer modelling, in a two-stage approach whereby thermal comfort (represented by the Index of Thermal Stress) is modelled using as input detailed microclimate simulated by a canyon model (CAT). The analysis suggests that although use of high-albedo materials in canyon surfaces may lower air temperature, the reduction is not enough to offset increased radiant loads. As a result, pedestrian thermal comfort may in fact be compromised.

Keywords: radiant exchange; computer modelling; energy balance; CAT model; Index of Thermal Stress

INTRODUCTION

When the temperature of the ground surface is warmer than that of the canopy layer air, the direction of sensible heat flux is upward, leading to an increase in near-surface air temperature. Unlike many rural areas, where plant cover and evaporation of soil moisture may moderate the increase of surface temperature that occurs when solar radiation is absorbed, a large proportion of urban areas consists of dry impervious materials – pavement or buildings. To mitigate the temperature increase displayed by such surfaces, which results in warmer air temperature, several researchers [1-3] have suggested that wherever possible, they should have a high albedo. The implicit assumptions of this strategy are that by lowering canopy layer air temperature, cities will enjoy a) reduced air conditioning loads in buildings; and b) improved thermal comfort for pedestrians in outdoor urban spaces. The aim of this paper is to examine the second of these assumptions by means of computer modelling.

METHODOLOGY

Pedestrian thermal comfort was modelled in a two-stage approach: First, the CAT model [4] was used to predict the effect of altering surface albedo on air temperature, relative humidity, wind speed and surface temperatures in a street canyon. The predicted values were then used in the ITS model [5**,**6] to assess the effect of albedo modification on the thermal stress of a pedestrian in the street, considering changes in net radiation, convection and sweat efficiency. The analysis was carried out for streets of varying aspect ratio and orientation, in a hot-arid location.

The Canyon Air Temperature model (CAT)

The CAT model uses meteorological data from a representative (non-urban) weather station in the region to generate time series of local-scale meteorological parameters at an urban street canyon. The transformation is based on a complete surface energy balance at the two sites: In addition to a 2.5-dimensional analysis of radiant exchange accounting for short and long-wave fluxes, it incorporates several elements of the LUMPS parameterization scheme [**7**], including moisture advection from nearby vegetation and bodies of water, as detailed in Erell et al [**8**]. The effect of turbulent mixing in different stability regimes is estimated by means of an empirical correlation established using site data from Adelaide and Goteborg.

Index of Thermal Stress (ITS)

The ITS is a measure of the rate at which the human body must secrete sweat in order to maintain thermal equilibrium under warm conditions, in response to both metabolic heat production and heat exchange with the environment [9]. It is defined as the ratio between the rate of sweat evaporation required for thermal equilibrium and a cooling efficiency that is estimated by an empirical relationship that accounts for the humidity of the air, wind speed and the insulation value of the clothing. To obtain the ITS, a full energy balance must be evaluated for the pedestrian, approximated by a rotationally symmetrical standing body: The calculation includes short-wave radiation (direct, diffuse and reflected from adjacent surfaces, as well as reflected from the skin); long-wave radiation (received from the sky and from terrestrial surfaces, and emitted by the skin); and convection with the surrounding air [5]. The level of pedestrian thermal stress yielded by the ITS is given in watts (W), and values of the index may be correlated with categories of subjective thermal sensation ranging from "comfortable" to "very hot" based on threshold values that were recently validated and refined using observational data [6].

Simulation parameters

Pedestrian thermal comfort was modelled for the cities of Eilat (Israel) and Adelaide (Australia) on typical summer days (July 22 and Nov. 25, respectively). The climate of Eilat (29.55N 34.95E) is hyper-arid (Koppen BWh), while Adelaide has a hot Mediterranean climate (Koppen Csa). Reference weather data were obtained in the form of TMYs generated by the respective national weather services from observations carried out at stations located near the cities. In both locations, the urban sites simulated were actual pairs of intersecting streets.

The analysis examined the effect of the following parameters (a total of 24 scenarios for each city):

- Canyon aspect ratio: canyon walls were kept at a height of 10 meters, and the width of the space was varied from 5 meters, to 10 meters, 20 meters and 100 meters (H/W = 2, 1, 0.5 and 0.1).
- Canyon direction: north-south and east-west.
- Surface albedo: the road surface and both walls were assigned equal albedos of 0.2 (corresponding to asphalt); 0.45 (concrete); and 0.7 (whitewash). Although the former value is very low – wall surfaces are rarely so dark, and the latter very high – it is impractical to maintain roads at a bright white finish – these values represent extreme combinations that will magnify any potential effect of albedo modification.

SIMULATION RESULTS

As indicated above, evaluating the thermal sensation of pedestrians in urban street canyons requires integrated modelling of several inter-related parameters. An illustration of model inputs to ITS generated by CAT will be presented first, in isolation; some intermediate results of ITS calculations will be presented next; finally, an attempt will be made to tie all of the effects together in a comprehensive framework.

Effect of albedo change on surface temperature

The effect of albedo change on modelled surface temperatures is illustrated in Figure 1, for the canyon floor of a N-S street in Eilat, Israel, with an aspect ratio H/W=1. Although all surfaces are warmer than the air, the difference between a dark floor surface and a light one is as much as 25K. Data (not shown here) indicate that walls facing east are warmer in the morning, and those facing west in the afternoon, with differences due to albedo reaching 15K. It is worth noting that the surface of the exposed desert soil at the weather station is, in the case of Eilat, warmer than the street surface throughout the day, except for a short period after mid-day in the case of the darkest colour. This is because the albedo of the soil is about 0.35, and it is exposed for the duration of the daylight hours, unlike the street which is shaded for much of the day.

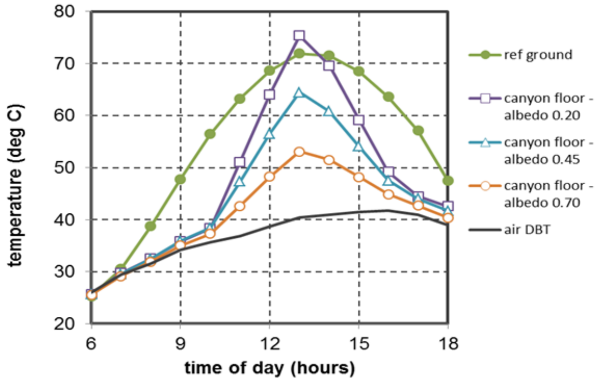


Figure 1. Effect of albedo on modelled temperature for pavement of a N-S street canyon with H/W=1 (Eilat, Israel).

Effect of albedo change on air temperature

The effects of albedo modification on air temperature at all locations were minor: The maximum reduction in air temperature between the high-albedo scenario and the low-albedo one at 12:00, when solar radiation levels were highest, was estimated at 0.7-1.0 K, in the open space (canyon H/W=0.1). In deep canyons (H/W=2), the effect is much smaller, and was estimated at 0.2-0.3 degrees only [9].

Figure 2 illustrates the case of Adelaide, where the CAT simulation predicts that air temperature in the street canyon will be higher than at the reference weather station at night and slightly lower during the daytime. The modest daytime cool island predicted is probably due to the effect of shading by canyon walls and of thermal mass, and was also observed in actual monitoring that took place at the sites [10].

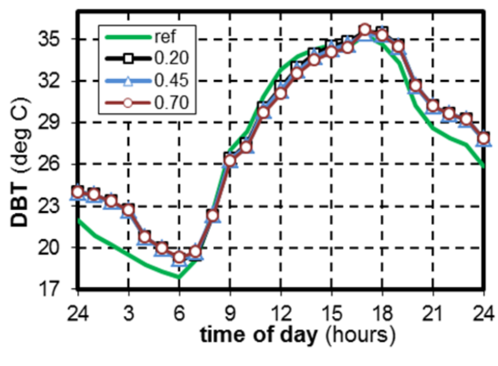


Figure 2. Dry bulb temperature measured at the weather station (ref) and simulated temperature in an E-W street canyon with H/W=1, for different surface albedos (data for Adelaide).

The effects of albedo modification on air temperature were minor: The maximum difference between the high-albedo scenario and the low-albedo one, which was predicted to occur at about 14:00, was 0.8 K for the open space (H/W=0.1), and only 0.2 K in the case of the deep canyon (H/W=2).

Environmental stress on pedestrians

The ITS model uses a cylinder to represent the form of a (standing) pedestrian. The effect of changing the albedo of canyon surfaces on the heat load imposed by the environment is shown in Figure 3. Increasing albedo results in changes to the composition of this load: reflected sunlight (SW) contributes more to the overall heat flux on a pedestrian, while the long wave (LW) component decreases. The increase in the net radiant load is only partially offset by the small reduction in air temperature, so the total load is also slightly larger.

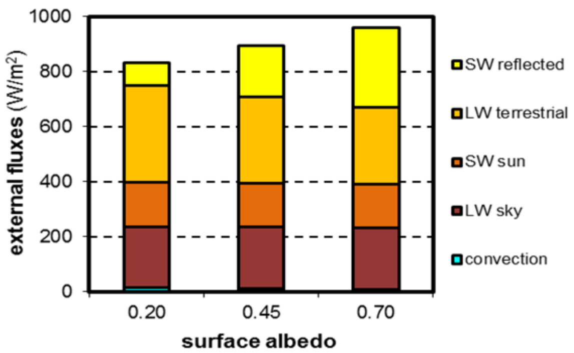


Figure 3. The external heat fluxes calculated for a pedestrian at the middle of a square (approximated by an E-W canyon with H/W=0.1) at noon on a typical summer day. (data for Eilat, Israel)

Note too that direct sunlight ('SW sun') comprises a relatively small proportion of the incident flux, because at high solar elevations, the cross-sectional area of a person exposed to it is relatively small (primarily the top of the cylinder). Most of the radiant energy, both shortwave and long wave, is absorbed by the side of the cylinder. Finally, because air temperature at this time was approx. 36^{o}C, convection is negligible – so the body may be cooled only by evaporation of sweat.

Pedestrian thermal comfort

The thermal stress on a pedestrian (in warm conditions) is determined by the balance between the external radiative and convective loads (Fig. 3) and the internal metabolic heat production, on one hand, and the cooling provided by the evaporation of sweat on the other. Figure 4 shows the effect of surface albedo on this balance.

Cooling efficiency is affected by wind speed and humidity – but not by albedo (except in an indirect way, through modification of air temperature) - so any increase in environmental load on a pedestrian is reflected in the heat stress, too. Although solar radiation peaks at about midday, heat stress reaches a maximum later in the afternoon: lower solar altitude results in more direct and reflected sunlight hitting the vertical surface of the cylinder representing the human body (compared to its top); surface temperature increases so the long wave load is still high; and air temperature is highest.

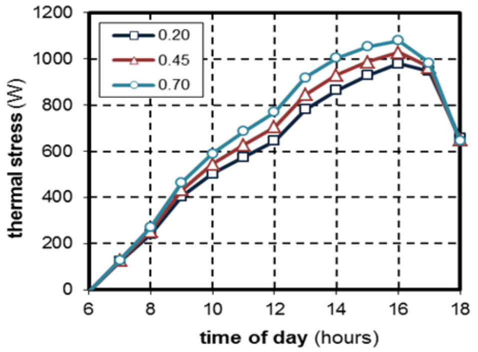


Figure 4. Effect of surface albedo on the net thermal stress imposed on a pedestrian in an E-W street with H/W=1.

Effect of canyon aspect ratio

The aspect ratio of the street canyon alters the composition of the incoming radiant flux: A pedestrian in a narrow street will be less exposed to direct or diffuse solar radiation, and the value of surface albedo will then determine the exposure to reflected radiation. Exposure to long wave radiation depends on the view factors of the sky and of each of the canyon surfaces, as well as their temperature – which will be influenced by the amount of solar radiation absorbed. Finally, canyon aspect ratio also affects airflow, and thus convective exchange and the cooling efficiency by sweating (which are not affected by albedo, if one ignores the effect of differential heating of canyon surfaces on the lee vortex).

Figure 5 illustrates the effect of canyon aspect ratio in the case of narrow N-S streets.

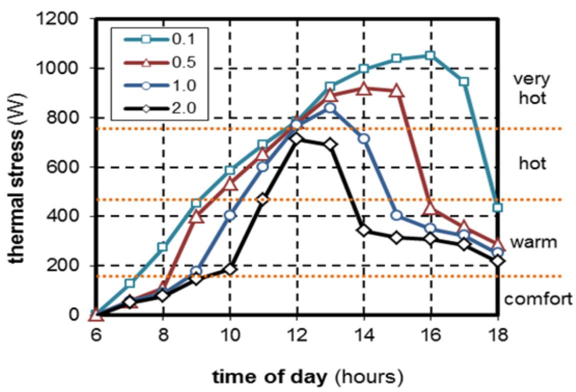


Figure 5. Effect of canyon aspect ratio on the net thermal stress on a pedestrian in a N-S street with albedo=0.7.

As the figure shows, pedestrians in narrow canyons will be exposed to much lower maximum levels of heat stress than their counterparts in exposed spaces, and will be exposed to such high stress for a much shorter time span.

Table 1 demonstrates that this is the case for all values of surface albedo: Higher albedo results in more heat stress in all canyons, wide or narrow.

Table 1: Effect of aspect ratio and albedo on the maximum pedestrian thermal stress (W) in a N-S canyon.

	Surface albedo		
H/W	**0.20**	**0.45**	**0.70**
0.1	964	1006	1051
0.5	853	884	918
1.0	774	808	840
2.0	709	696	713

Effect of canyon orientation

The orientation of a street canyon affects the timing of exposure to direct sunlight, particularly if it is narrow: in a N-S canyon a pedestrian will be exposed near mid-day, but shaded in the early morning and late afternoon hours; in an E-W canyon, they will be exposed mainly in the morning and afternoon, but also at mid-day if the sun is sufficiently high, as is the case in most hot climates during summer.

These observations are the result of purely geometrical considerations, and as Figure 6 illustrates, the effect of surface albedo on overall thermal stress is fairly small. The direction of these differences, in both orientations, follows that seen previously: an increase in the reflected component of sunlight results in greater thermal stress during periods of maximum exposure.

DISCUSSION

The present study suggests that the use of high-albedo materials in urban surfaces may not have the unequivocally favourable outcome predicted by most previous studies. In particular, although both air temperature and surface temperatures are impacted in predictable ways that are broadly in line with most other studies, the detailed and comprehensive analysis of all of the environmental fluxes has yielded fresh insights. The following discussion provides some perspective on these findings.

Limitations of the models

CAT models micro-scale effects, but albedo modification may also have cumulative effects at the urban scale. The magnitude of this effect may depend on factors such as the extent of the area treated and the intensity of the incoming solar flux [**11**]. Most studies suggest that extensive use of high-albedo materials may result in a reduction of peak daytime temperatures by about 2**°C** [2], although a localized decrease of as much as 4.5**°C** may be experienced in certain conditions [1].

The sensitivity of the results presented in this study to the beneficial cumulative effects of extensive albedo modification was therefore tested by running the ITS model again, imposing a temperature reduction of 2°C relative to the temperature data predicted by CAT in the case of high-albedo surface, and comparing the resulting heat stress for the two configurations. As Figure 7 shows, the effect of the temperature reduction on the heat stress of a pedestrian, although measurable, is in fact quite modest in these conditions.

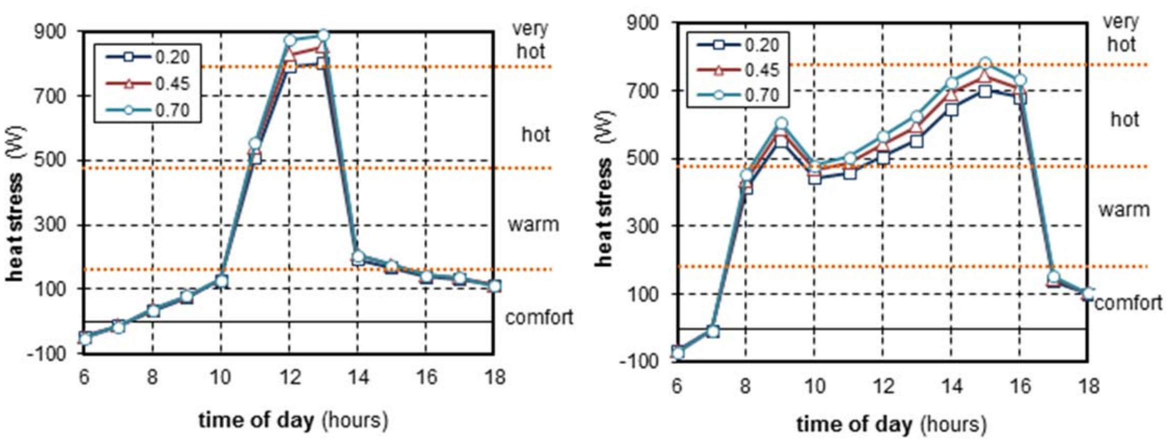


Fig 6. Effect of canyon orientation (N-S canyon, left and E-W canyon right) on net pedestrian thermal stress, with threshold values of ITS separating categories of subjective thermal sensation. (Data shown for a pedestrian in a street with H/W = 2 in Adelaide, Australia).

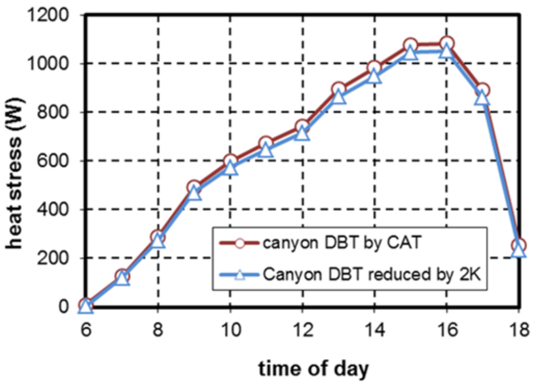


Figure 7. Effect of a DBT reduction of 2K on the net thermal stress imposed on a pedestrian in an E-W street with H/W=1 and albedo=0.7.

Neither CAT nor ITS model the effects of in-canyon vegetation on radiant exchange or air speed: The canyon modelled in this study is in fact devoid of any obstruction. However, it should be noted that where vegetation is plentiful the potential for microclimate modification by application of high-albedo surfaces is likely to be small, in any case: Shade cast by trees minimizes any potential gains from increased reflection of direct sunlight; and, while surfaces covered by plants have a low albedo, they are cooler than paved surfaces and have a favourable effect on thermal comfort.

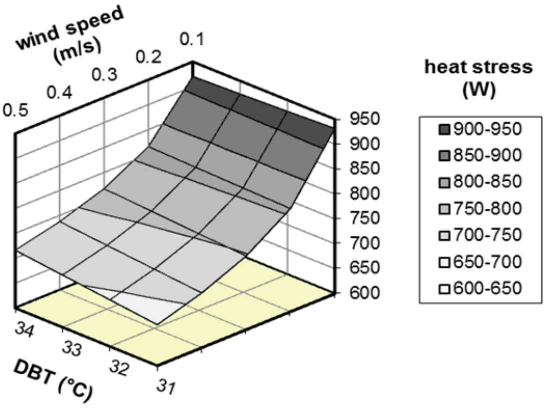
In calculating the ITS, it is assumed that the body is exposed and the effects of clothing are minimal. As Figure 3 shows, in warm weather, when the difference between air temperature and skin temperature is small, the contribution of convection to the energy balance is also correspondingly small. Clothing may, however, have a substantial beneficial contribution in warm climates too, by reducing exposure to radiant gain - especially if gains are reflected (as in the case of light-coloured clothing). However, clothing also restricts air flow near the skin, reducing the efficiency of cooling by evaporation of sweat. The balance of these two counter-acting effects determines whether the clothing in question contributes to thermal comfort.

Using a simplified rotationally symmetrical form to represent the human body's DuBois area [5] takes no account of the increased sensitivity of some body parts (e.g. the face) or variations in body shape and posture. While such physiological variations have been considered by detailing the area projection factors of separate bodily components [12], their effect on the overall energy balance of the body is secondary.

Sensitivity to other environmental factors

The ITS expresses the sum of radiant and convective exchanges, as modified by the body's ability to dissipate excess heat through evaporation of sweat. The latter is affected by humidity, as well as by temperature and wind speed – all of which are encapsulated in the sweat efficiency factor (f) [5], which is affected by all of these environmental parameters, in addition to a clothing factor. The contribution of wind speed, for example, is especially important when both air temperature and relative humidity are high, and the body's ability to lose excess heat by sweating is limited.

As Figure 8 shows, the effect of a 2-3 degree increase in dry bulb temperature is relatively small.



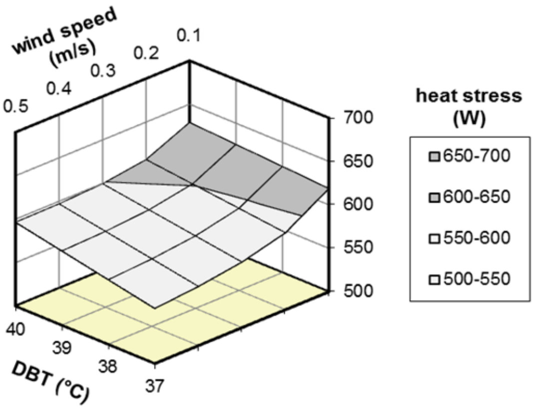


Figure 8. Effect of wind speed on pedestrian thermal stress (W) at noon in an open square (H/W = 0.1), assuming global horizontal flux of 900 wm^{-2}, diffuse solar radiation 200 Wm^{-2}, and surface albedo = 0.45.
In the case of Adelaide (top) the data are for Nov. 25, with a vapour pressure of 24.6 mmHg (equivalent to DBT=31^{o}C and RH=65%). In the case of Eilat (below), the data are for July 22, with a vapour pressure of only 15.0 mmHg (equivalent to DBT=37^{o}C and RH=11%).

However, in warm humid conditions, illustrated for the case of Adelaide, if air flow adjacent to the body drops below about 0.5 m/s (and especially below about 0.2 m/s), the body may find it difficult to lose excess heat, leading to extreme heat stress. In hot but very dry conditions, illustrated for the case of Eilat, evaporation of sweat remains effective even in the absence of wind.

This highlights the importance of comprehensive modelling of all environmental factors that affect thermal comfort: the potential for error when air temperature alone is considered, as is often the case, may be large.

Thermal sensation at any given point in space and time is also affected by other factors, including aliesthesia (change in perception compared to the previous environment a person was exposed to) and visual comfort [6]. Thermal preferences also vary among individuals. The present study, while acknowledging the importance of all of these factors, is limited to assessing the thermal balance only, emphasizing the relative role of the various components of this balance.

Application in urban design

Extensive use of high-albedo materials has been advocated as a means of mitigating the urban heat island. The results of this study indicate that local benefits, in terms of pedestrian thermal comfort, are likely to be marginal, at best. Furthermore, since a measurable effect on urban air temperature is dependent on large-scale application of such materials, streets where renovation is carried out first are likely to experience negative effects, until the cumulative effects of city-wide changes begin to take effect. Planners and the public need to be aware of this: High expectations that are not fulfilled may lead to disillusionment and abandonment of the policy prematurely.

CONCLUSION

Although use of high-albedo materials in urban surfaces may reduce the air temperature to which pedestrians are exposed, this change has only a small effect on their thermal balance with the environment: The reduction in surface temperatures, which leads to reduced long-wave emission, is offset by increased reflection of solar radiation. The net effect of increasing the albedo of urban surfaces may thus be a small increase in the thermal stress to which pedestrians are exposed – rather than the expected improvement in thermal comfort.

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