10C.6

THE INFLUENCE OF FACADE PROPERTIES ON THE CANOPY LAYER MICROCLIMATE WITHIN CITY BLOCKS

Csilla V. Gál*
Illinois Institute of Technology, Chicago, IL

1. INTRODUCTION

The application of high albedo surfaces and 'cool' materials — characterized by high solar reflectance and emissivity — are often advocated as a means to mitigate the urban heat island (UHI), to decrease indoor temperatures and consequently to reduce cooling loads in warm weather. The frequently described mechanism that links higher surface albedos with lower outdoor temperatures emphasizes the role of decreased surface temperatures in the process. Admittedly, the high albedo approach to UHI mitigation is primarily recommended for roofs, which, compared to roads and facades, have less obstructed sky views. During the day, the higher sky view factor of roofs prevents the trapping of radiation within the urban texture, and ensures a better radiative cooling by night. Nevertheless, the high albedo approach and the application of `cool materials' are increasingly recommended for both urban roads (Akbari, Pomerantz, and Taha 2001; Alchapar, Correa, and Cantón 2014; Santamouris et al. 2012; Santamouris, Synnefa, and Karlessi 2011; Synnefa et al. 2011; Zinzi, Carnielo, and Fasano 2012) and facades (Bougiatioti et al. 2009; Doya, Bozonnet, and Allard 2012; Synnefa, Santamouris, and Apostolakis 2007). The goal of this study is to investigate the role of facade surface properties on the canopy layer microclimate in a dense urban context.

2. MATERIALS AND METHODS

In order to assess the impact of facade materials on the microclimate within urban blocks a numerical simulation study was conducted. The study utilized ENVI-met Version 3.1 BETA V for microclimate simulation and MATLAB Version 7.12 for the analysis of the results. The applied research methodology consisted of two phases: during the first, the cases were selected and the baseline case developed, while over the second phase the results were analyzed.

2.1. Model domain and configuration

Four denser urban block typologies from Budapest were selected for the study: the nineteenth-century configuration consisting of attached courtyard apartment buildings (T1), the perimeter block built up at its edges (T2), the Zeilenbau design of parallel rows of buildings (T3), and the hybrid form composed of a set of short towers placed atop of a unifying base (T4). The cases and their model equivalents are illustrated in Figure 1 and 2, respectively. Each model consists of nine identical urban blocks arranged in a three-by-three grid layout. The urban blocks are 78 m wide and 150 m long, and are separated by 18 m wide roads. Building heights are 24 meters uniformly — except for the base in the hybrid configuration, which is set to 6 meters. The models have a 6 m horizontal and 3 m vertical resolution is. In terms of ground surface materials, gravel asphalt is assigned to roads, whereas open areas within the blocks are left as unsealed silt-loam soil.

Figure 1: The block of courtyard apartments, the perimeter block, the Zeilenbau configuration and the hybrid block (Google Maps 2010).

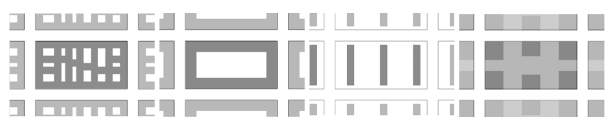

Figure 2: The model equivalents of the four typologies: T1, T2, T3 and T4

Since ENVI-met disregards the thermal capacity of building materials, the influence of three facade parameters were evaluated by the study: the thermal transmittance, the surface albedo and the fenestration ratio. In order to evaluate the effects of these parameters individually, the selected values were applied to the initial scenario gradually: first, an improved U-value only; second, a higher albedo only; third, both the improved U-value and the high albedo; and finally, a chosen fenestration ratio was applied, which modified both the facade albedo and the thermal transmittance. Thus, beyond the initial scenario, the method resulted four additional scenarios per each case (see Table 1 with the selected facade parameters).

Since the baseline case mimicked rural conditions, it did not contain buildings. It was developed to emulate a typical July day in Budapest (see Gál 2014a) and supplied the reference or background climate conditions

* *Corresponding author address*: Csilla V. Gál, College of Architecture, Illinois Institute of Technology, Chicago, IL 60616-3793; e-mail: cgal@hawk.iit.edu

utilized in the analysis. The comparison of obtained and reproduced typical air temperature and specific humidity cycles are illustrated on Figure 3.

Table 1: Façade properties and scenarios

Scenarios		**U [W/m^{2}k]**	**a []**	**w [%]**
-	initial	1.10	0.40	
U	U-value only	0.30	0.40	
a	albedo only	1.10	0.80	
Ua	U & albedo	0.30	0.80	
w	fenestration	0.80	0.55	35

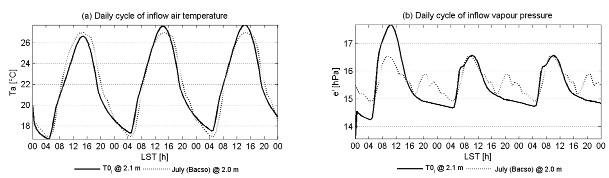

Figure 3: Comparison of ENVI-met simulated (baseline case) and average July conditions in Budapest, Hungary (Bacsó 1959): (left) potential air temperature, (right) vapor pressure

2.2. Method of analysis

The study follows a standard procedure in numerical modeling. First, in order to minimize the edge effect, the analyses only consider conditions within the central urban block (out of the three-by-three layout). Second, since ENVI-met has a rather long spin-up time, only the second day results are evaluated. Finally, in an attempt to reduce systematic model errors, results are reported relative to the baseline.

Since radiation and air temperatures are key parameters governing human thermal comfort and surface temperatures during clear and calm conditions, potential air temperature and mean radiant temperature (T_{MRT}) are chosen as indicators of the canopy layer microclimate for the study. The presented analysis utilizes volumetric median air temperatures (ΔT_{UCL}) and mean radiant temperatures ($\Delta T_{MRT\text{-}UCL}$) calculated for the UCL above the central urban block relative to the baseline condition. The characteristic urban heat island measures --- the diurnal temperature range (DTR) reduction, the nighttime and the daytime heat island intensity --- are similarly calculated for the entire UCL above the block, are also discussed by the study (for additional details see Gál 2014).

In order to manage the spatial and temporal complexity of urban microclimates, the study adopted a simple method based on areal average values (Gál 2014b; 2014a). This concept consists of areal medians calculated for every elevation within the selected UCL and for every time step of the numerical simulation (see Figure 4). The areal canopy medians, calculated relative to the baseline, are assembled into a matrix with results from different elevations arranged into vertical columns and with results from different times joined into rows. The magnitude of the calculated parameters is indicated by colors. The advantage of this representation is that it provides a more detailed overview of the diurnal evolution of UCL conditions, while at the same time retaining the relative positions of adjacent air layers.

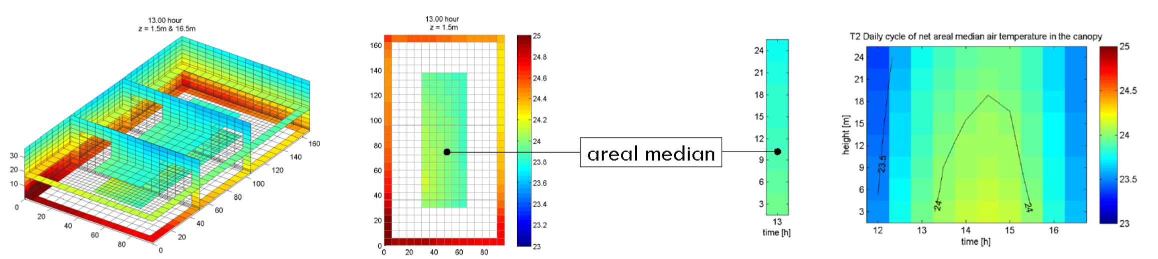

Figure 4: The method of producing pseudocolor plots from areal median air temperature values

3. RESULTS AND DICUSSIONS

3.1. The influence of form

As the influence of built form on the canopy layer microclimate has already been discussed previously (Gál 2014a; 2014b), here an overview is provided only necessary for subsequent analyses. Figure 5 presents the characteristic urban heat island measures calculated for the initial scenario (see Table 1). With less than 0.5°C_DTR reduction the Zeilenbau configuration (T3) modifies the background climate the least. In the case of the other configurations it is around 3°C (see Figure 5a). Night and daytime UHI magnitudes indicate further differences between the latter three cases. According Figure 5b and 5c, the diurnal cycles of T1, T2 and T4 are offset by about 0.3°C: the warmest configuration is T4 and the coolest is T1. T4 is also characterized by the highest nighttime UHI intensity (nearly 1.5°C), whereas T1 exhibits the coolest daytime temperatures and has an over 2°C 'cool island' intensity.

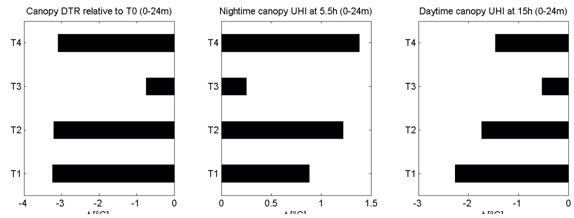

Figure 5: DTR reduction, day- and nighttime UHI magnitudes for all four typologies, calculated relative to the baseline condition

Canopy layer conditions within the initial urban blocks are presented on Figure 6. Potential air temperature trends (Figure 6a) are in line with the above observations: the initial configurations remain warmer at night and cooler at day than the baseline case. In the case of T3, both daytime temperature reduction and nighttime temperature excess remain below 1.2°C. Here, the low building density and the openness of the configuration no only allow for radiative and convective cooling at night, but also contribute to higher temperatures during the day: the lack of shading increases both surface and air temperatures, while the lack of enclosure ensures that the warm canopy air remains well-mixed. In contrast, daytime cooling is strongest in the case of courtyard typologies (T1 and T2), as the air in courtyards remains separated from the relatively warmer air of the street. During the hottest hours of the day, the cooling intensity of T1 configuration exceeds 3°C at the bottom of the small courtyards.

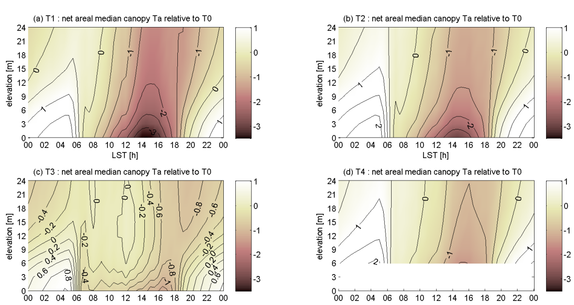

Figure 6a: Potential temperatures cycles within the UCL relative to the baseline (initial scenario)

The effects of built form on the radiation fluxes within the canopy are shown in Figure 6(b). In all four cases, the radiation reductions around sunrise and sunset are the result of shortwave radiation obstructions at low sun angles. In configurations with large open spaces (T2, T3), the effect of shading ceases during high sun hours. In the case of T4, the interference between the towers decreases radiant temperatures by more than 15°C around midday. Solar obstruction is greatest at the configuration with small courtyards (T1). Here, the icicle shape pattern around noon signals the average depth solar radiation reaches down the courtyards.

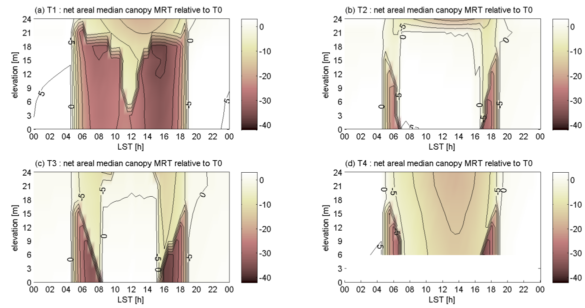

Figure 6b: Mean radiant temperatures cycles within the UCL relative to the baseline (initial scenario)

3.2. The effect of façade properties

The influence of facade material properties on the diurnal cycle of median canopy air temperatures is presented in Figure 7a. The initial and the four additional scenarios are grouped by configurations. Since change in U-values did not modify the diurnal cycles significantly, the scenarios with modified U-values (U-value only and the U-value plus albedo scenarios) were plotted with dots only in order to make the line of the nearly identical scenarios visible. With the albedo governing the thermal conditions within the UCL, all sub-figures indicate the same trend: the albedo's effect is most pronounced during the day and the relationship between the albedo and the potential temperature is directly proportional (although this proportion is slightly different in each configuration). The effect of facade properties on the MRT cycles is presented in Figure 7b. Similarly to potential temperatures, radiant temperatures within the canopy are primarily driven by surface albedo changes and remain scarcely influenced by facade thermal transmittance. The relationship between the TMRT and albedo is directly proportional with effects largely limited to daytime. The uneven impact of albedo in time and per configuration indicate that canopy layer TMRT is the function built form and facade density. However, this relationship needs further investigation in the future.

A better comparison of thermal canopy layer conditions for all four configurations and five scenarios is provided by are the urban heat island measures in Figure 8. Regarding to the role of different surface parameters similar observations can be made as above: albedo determines the conditions within the UCL, the influence of thermal transmittance is negligible and the effect of fenestration ratio is exerted though the albedo (increasing fenestration decreases the albedo of walls). The cross comparison of the cases also reveals that while facade properties affect the conditions within the canopy, these influences are only secondary to the impact of form.

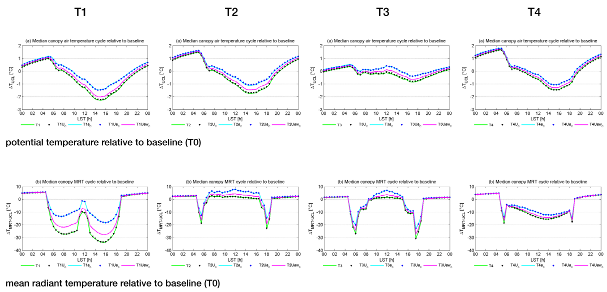

Figure 7: The influence of facade material properties on the diurnal cycles of relative canopy layer potential air temperatures and mean radiant temperatures, plotted for all typologies and cases

As the direct relationship between surface albedo and air temperature is not a result that would be generally expected on the basis of related literature, conditions within the canopy are further analyzed using areal average method. In the remaining part, the effects of facade properties on the UCL microclimate are discussed through the example of the courtyard apartment typology (T1). Since facade properties within a given configurations cause relatively small changes when using the baseline case as a reference, subsequent analyses will use the initial scenario of the selected configuration as a reference. The change largely removes the influence of built form the picture and highlights the influence of surface properties. Additionally, as the changes remained still rather small, the color scales of the plots were also adjusted for better visualization.

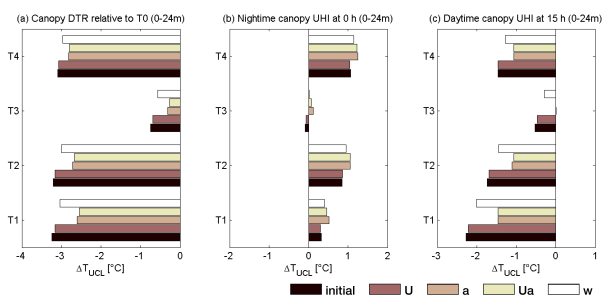

Figure 8: The influence of facade material properties on the (a) DTR reduction, (b) day- and (c) nighttime UHI magnitudes, calculated relative to the baseline condition. The bars from the bottom up indicate: black - initial setup; dark gray - U-vales; mid gray - albedos; light gray - thermal transmittance and albedos; white - fenestration ratio

Figure 9a shows the diurnal trend of median potential temperatures within the canopy for T1 for different material property scenarios. The almost entirely dark figure on the left demonstrating no change (U-value only scenario) and the nearly identical middle figures (albedo and albedo with U-value scenarios, respectively) indicate that thermal transmittance has a negligible effect on the UCL microclimate. The increasing albedo increase canopy temperatures, especially during the early afternoon and towards the bottom of the courtyards. In the case of the greatest albedo scenarios (central figures) the increase in median canopy layer temperature is close to 1°C near the ground.

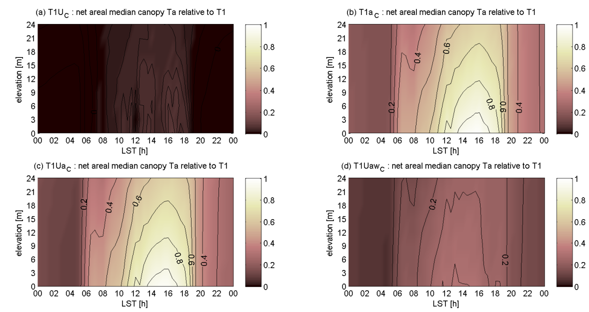

Figure 9a: The influence of facade material properties on T1's diurnal course of relative areal median air temperatures within the canopy, plotted relative to the initial T1 configuration

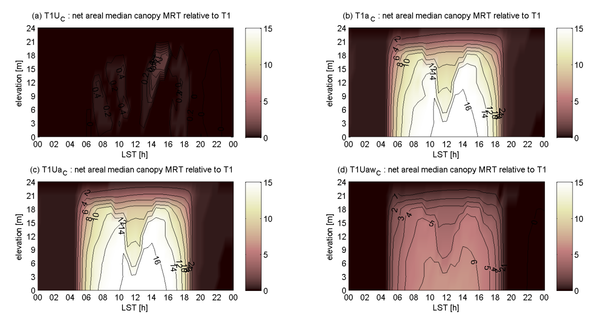

Figure 9b: The influence of facade material properties on T1's diurnal course of relative areal median MRT within the canopy, plotted relative to the initial T1 configuration

The effect of facade properties on the median radiant temperatures within the UCL of T1 is presented in Figure 9b. With the albedo governing the canopy layer conditions, the general trends are similar as above. The influence of albedo can be described as follows: higher values increase the ratio of reflected solar radiation within the UCL, which in turn increases mean radiant temperatures. In this case, the greatest albedo change of +0.4 increases median radiant temperatures by over 16°C at the bottom of the canopy during early afternoon. The T_{MRT} patterns also indicate interplay between shortwave radiation and built form: the effect of high facade albedo grows with increasing solar angles until the sun is able to shine down the small courtyards and irradiate the ground (with unchanged reflectance). The decreasing influence of facade albedo with elevation indicates that reflected radiation plays a greater role in obstructed places with low sky view factors.

Based on these results, the likely mechanism behind the rising canopy layer temperatures that contradict the cooling effect of high albedo surfaces generally alluded to in the literature is as follows. Although higher albedos decrease surface temperatures and thus reduce convective and radiative heat transfers to the ambient air, they nevertheless increase the amount of radiation reflected further down the canopy. Trapped between buildings, an increased amount of reflected radiation is absorbed by the canopy floor --- in our case by the unsealed ground within urban blocks. Since canopy floors are generally obstructed (i.e. characterized by low sky view factor), it is likely that a considerable part of this absorbed extra energy is dissipated as sensible heat. While this `floor heating' hypothesis needs further investigation, this explanation is partially supported by the above noted trends of decreasing potential air and mean radiant temperature with elevation (see Figure 7a and 7b).

4. CONCLUSIONS

A numerical simulation study was undertaken to investigate the effect facade material properties on the microclimate within urban blocks. The results indicate that among the three assessed parameters albedo drives the UCL microclimate. Changes in facade albedo are found to be directly proportional with changes in air and radiant temperatures. The impact of fenestration ratio is exerted though the albedo indirectly, as increasing fenestration ratio decreases the albedo of walls. The effect of heat transmission coefficient on the UCL microclimate is marginal. The study also found that the influence of built form is more decisive than that of facade properties.

The results also indicated that increasing facade albedos might have unintended consequences in the canopy, as they increase both potential air and mean radiant temperatures. The likely explanation for this phenomenon is 'ground heating' due to radiation trapping. However, since ENVI-met neglects the heat capacity of building materials in deriving surface temperatures, the obtained results likely contain errors. The studies of (Ali-Toudert 2005; Malekzadeh 2009; Malekzadeh and Loveday 2008) indicate that surface temperatures, along with the temperatures of adjacent air layers, do not follow trends observed on the field. Due to the lack of thermal storage, surfaces in the model warm up (cool down) faster when irradiated (become shaded) (Malekzadeh 2009). Furthermore, air temperatures in the courtyard (Malekzadeh and Loveday 2008) and in the urban canyon (Ali-Toudert 2005) were found to be almost uniform, without significant warming near the irradiated surfaces. Nevertheless, the findings of this study indicate that within the urban canopy high reflectance materials should be applied with caution.

ACKNOWLEDGEMENTS

This work was partially supported by the 2010--2011 James A. Speyer Scholarship. The author is grateful to the Anstiss and Ronald Krueck Foundation for their support.

REFERENCES

Akbari, Hashem, Melvin Pomerantz, and Haider Taha. 2001. “Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas.” *Solar Energy* 70(3): 295–310.

Alchapar, Noelia L, Erica N Correa, and M Alicia Cantón. 2014. “Classification of Building Materials Used in the Urban Envelopes According to Their Capacity for Mitigation of the Urban Heat Island in Semiarid Zones.” *Energy and Buildings* 69: 22–32.

Ali-Toudert, Fazia. 2005. “Dependence of Outdoor Thermal Comfort on Street Design in Hot and Dry Climate.” eds. Helmut Mayer and Andreas Matzarakis. Meteorologischen Instituts der Albert-Ludwigs-Universität Freiburg. http://www.meteo.uni-freiburg.de/forschung/publikationen/berichte.

Bougiatioti, F, E Evangelinos, G Poulakos, and E Zacharopoulos. 2009. “The Summer Thermal Behaviour of ‘Skin’ Materials for Vertical Surfaces in Athens, Greece as a Decisive Parameter for Their Selection.” *Solar Energy* 83(4): 582–98.

Doya, Maxime, Emmanuel Bozonnet, and Francis Allard. 2012. “Experimental Measurement of Cool Facades’ Performance in a Dense Urban Environment.” *Energy and Buildings* 55: 42–50.

Gál, Csilla V. 2014a. “The Impact of Built Form on the Urban Microclimate at the Scale of City Blocks.” In Atlanta, GA. https://ams.confex.com/ams/94Annual/webprogram/Paper236436.html.

Gál, Csilla V. 2014b. “The Influence of Built Form and Vegetation on the Canopy Layer Microclimate Within Urban Blocks.” *Acta Climatologica et Chorologica* 47–48: 43–52.

Google Maps. 2010. “Urban Blocks From Budapest, Hungary.” http://maps.google.com/.

Malekzadeh, Masoud. 2009. “Positioning of Outdoor Space in House Design - an Energy Efficiency and Thermal Comfort Perspective.” Loughborough University. https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/10301.

Malekzadeh, Masoud, and D L Loveday. 2008. “Towards the Integrated Thermal Simulation of Indoor and Outdoor Building Spaces.” In Cumberland Lodge, Windsor, UK.

Santamouris, M et al. 2012. “Using Cool Paving Materials to Improve Microclimate of Urban Areas--Design Realization and Results of the Flisvos Project.” *Building and Environment* 53: 128–36.

Santamouris, Mat, Afroditi Synnefa, and Theoni Karlessi. 2011. “Using Advanced Cool Materials in the Urban Built Environment to Mitigate Heat Islands and Improve Thermal Comfort Conditions.” *Solar Energy* 85(12): 3085–3102.

Synnefa, Afroditi et al. 2011. “Experimental Testing of Cool Colored Thin Layer Asphalt and Estimation of Its Potential to Improve the Urban Microclimate.” *Building and Environment* 46(1): 38–44.

Synnefa, Afroditi, Mat Santamouris, and K Apostolakis. 2007. “On the Development, Optical Properties and Thermal Performance of Cool Colored Coatings for the Urban Environment.” *Solar Energy* 81(4): 488–97.

Zinzi, Michele, Emiliano Carnielo, and Gaetano Fasano. 2012. “Solar Characterisation of Cool Asphalts to Mitigate Urban Temperatures.” In Dublin, Ireland.