STUDING THE EFFECT OF “COOL” COATINGS IN STREET URBAN CANYONS AND ITS POTENTIAL AS A HEAT ISLAND MITIGATION TECHNIQUE

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Abstract

Surface temperature measurements were performed in a deep street canyon, during summer period, in the center of Athens. Surface temperature was measured on an hourly basis, at several spots, in the external facades of buildings, pavements and at ground level inside an urban canyon. At the same time experimental data of air temperature were collected through extensive monitoring at four different heights in the center of the urban canyon. Based on these measurements air temperature vertical stratification was analyzed and interpreted as a function of the coating used.

Computational fluid dynamics (CFD) simulation were performed for evaluating surface temperature in the external facades of the buildings and at ground level in the urban canyon, for the coating used in the urban street canyon. CFD simulations based on the orientation of the street, the geometrical characteristic of the street (Height/Width), together with the type of coating used to define the surface temperature at different spot inside the canyon. At the same time air temperature was calculated in the center of the canyon for the specific four heights. Computational results were compared to field data in order to validate the accuracy of the CFD model used for the prediction both of surface and air temperature inside an urban street canyon. Secondly, by the means of the computational fluid dynamics model for the various types of “cool” coatings used for the buildings facades and smart materials for the ground level, i) air temperature was calculated at four different heights inside the urban canyon and ii) surface temperature in the canyons facades and at ground level. The calculated data have been thoroughly analyzed.

Aim of the work was the comparison between measurements of the vertical stratification of air temperature inside a deep street urban canyon with the calculated ones for different “cool” coatings and smart materials and give evidences for the possible mitigation of the heat island effect. The use of “cool” coatings in buildings has been estimated as crucial for the energy consumption and thermal comfort conditions in cities. Their albedo to solar radiation and emissivity to long-wave radiation, are very important parameters for the reduction of absorbed solar radiation and air temperature inside street canyons.

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KEYWORDS

Surface temperature measurements and calculated values, cfd tool, vertical stratification of air temperature, cool coatings

1. INTRODUCTION

“Cool communities” strategies reroof and repave in lighter colors and new materials in order to reduce air temperature in cities and decrease the increased heat island effect. Planting trees is also an effective way to cool communities, mainly effective if they shade buildings, though savings are significant if they merely cool air by evapotranspiration. It was estimated that 50% of the temperature decrease could be arise from planting trees and 29% could be the benefits from the lighter-colored roofs and 21% from the light-colored pavements (Rosenfeld et al., 1998). In this study it was indicated that “cool communities” strategies, can lead to air temperatures’ reduction in LA as much as 3^0C.

In a recent study a smaller scale project carried out to optimize the rehabilitation of specific urban zone in a dense urban area in Maroussi, Athens (Santamouris et al., 2012). The project dealt with the rehabilitation of a zone of 16,000 m2, using new high reflectivity pavements, green spaces and earth to air heat exchangers. The repaving consisted of colored asphaltic material presenting a reflectivity close to 0.35 in the place of paving surfaces consisted of black asphalt for roads and dark concrete tiles for pavements with albedo lower than 0.4. The initial colored concrete pavements with reflectivity of 0.78 replaced with natural reflective materials, marbles, and concrete pavements colored with higher reflectivity paints. Computational analysis indicated that the use of cool pavements may lead to a decrease of the peak ambient temperature in the build area by 1.2–2.0 degrees. The application of all measures may raise up to 3.4 degrees the decrease of the air temperature, in the area.

In this study we focus on two different tasks. The first task is the comparison between the measured and calculated values for the a) surface temperature for the initial coating of the pavements and b) the air temperature in the center of a deep street urban canyon. The second task of this work is the calculation of the surface and the air temperature, inside the deep urban canyon, by using a “cool” coating and the possible mitigation of the heat island effect in the specific urban area.

2. DESCRIPTION OF THE MEASUREMENTS

Measurements of several meteorological parameters were performed, during summer period, in the center of Athens. The mobile meteorological station of the University of Athens (Figure 1) was parted from: a) a vehicle and b) a telescopic mast PT8 Combined Collar Mast Assembly with extended height of 15.3 meters, retracted height 3.43 meters and maximum head load 15 kgr. The experimental site was a deep street urban canyon, which is oriented in the center of Athens with the long axis in a NW’N-SE’S direction (33^0 from real North counter-clockwise). The in-canyon measuring point was located in the middle of a cross-canyon distance, 20 m from the North intersection. The mean buildings height was 23 meters and the distance between buildings was equal to 8 meters. The geometrical characteristics of the street canyon were H/W=3 and L/W=6.9.

The first type of measurements was:

a) Air temperature measurements in the centre of the canyon. Miniature thermometers were placed on the telescopic mast at 3.5-7.5-11.5-15.5 meters, measured air temperature every 30 seconds. The miniature screen formed housing for a range of temperature sensing elements, proving weather protection while allowing the free passage of air b) Wind speed and direction measurements in the centre of the canyon. Anemometers were placed on the telescopic mast at 3.5-7.5-11.5-15.5 meters height, measured and recorded wind speed and direction every 30 seconds. Pulse output anemometer 10 Hz per knot, for recording the air wind speed inside the canyon and W200 Porton Windwane, $\pm 300^0$ ranges for recording the wind direction respectively. The meteorological data were monitored from 9:00LT-18:00LT each day of the experimental campaign, which lasted three consecutive days.

The *second type of measurements was:*

Hourly surface temperature measurements at a cross section in the middle of the street canyon. An infrared thermometer equipped with a laser beam used to measure the surface temperatures of the exterior building façades facing the canyon. Measurements were performed from the bottom to the top of both façades of the canyon in steps of 1-1.5 m. All measurements were performed from street level. In addition, the pavement and road temperatures were measured at different points along the width of the canyon. All measurements were performed on an hourly basis during the twelve experimental hours.

For the recording of the meteorological data acquisition modules have been placed inside the vehicle. LabView was the software used for the recording and storing of the meteorological data.

3. DEDCRIPTION OF THE CFD SOFTWARE

The efficient simulation of the thermal energy condition in the area of interest the detailed three dimensional tool ANSYS CFX 13 has been used. ANSYS CFX is an advanced general code computational fluid dynamics model that solves the Navier Stokes differential equations and turbulence by the finite elements technique in the 3D space. It is a commercial software package that handles very detailed 3D geometry with the ability to solve efficiently heat transfer and fluid flow phenomena. Its accuracy has been widely verified against experimental and theoretical tests (www.ansys.com). Advanced CFD models can calculate with a high degree of accuracy microclimatic parameters at every grid point of the meshed space. However, the more complicated is the geometry of the urban open space the more resources of input data and calculation are needed.

ANSYS CFD is managed by its own desktop (Workbench) that the user handles the whole simulation process. It can simulate in steady state or transient mode the microclimatic parameters', heat transfer and fluid flows' distributions in time and space. This is the ideal approach of the three dimensional urban environment.

Simulation setup constituted of four stages, 1) Geometry integration and domain definitions, 2) Meshing, 3) Physics definition and 4) Solution and result representation. The more detailed is the structural and 3D geometry of buildings, streets, pavements, urban equipment and vegetation the more representative and accurate simulation will be.

The meshed geometry is used to define the physical parameters in the area under consideration (CFX-Pre). Surfaces with materials (concrete, glass, pavement, water, trees) and properties (emission and reflection coefficients) have been defined. Turbulence was simulated by the Shear Stress Transport model with K-Turbulence KE and O-Turbulence frequency. Thermal energy was simulated by the discritised model in surface to surface and medium to surface modes. This takes into account opposite surfaces energy exchange that is very important in the heat balance of the open spaces in case of replacing conventional surfaces with cool materials. Solar radiation has been taken into account in slope and deviation through the top boundary. Boundary conditions were gathered by the experimental data (air temperature, wind speed and direction, radiation, surface temperatures) that have been described on the previous paragraph. The simulation time step (5 sec) and convergence criteria (10^{-4} RMS of residuals) have been defined under steady state and transient calculation. Finally, the results have been processed in the CFD Post provided by the software according to the required challenges.

4. COMPARISON BETWEEN MEASURED AND CALCULATED VALUES

For the purpose of this study measurements inside the canyon estimated for 2-5.5-9.5-15.5 meters height since the levels where surface temperature was measured at the canyons' walls were 2.5-6-9.5-13-15.5-20 meters. It is important all measurements to be in the same level so differences between air and surface temperature to derive. The following equation (equation 1) can be used for the calculation of air temperature, where T_1 and T_2 are the temperatures at two heights Z_1, and Z_2 and a is the angle of elevation of the sun

$$T_1 - T_2 = N(1.2 - 6.8\sin a)\log_{10}(Z_1 / Z_2) \qquad (1)$$

where N is the effective absence of cloudiness (N= 1 corresponding to a clear sky). The angle of elevation of the sun was calculated for all the experimental days (Tait, 1949; Georgakis et al., 2010).

Measurements depicted in box plots. The line in the middle of the box is the median, or the 50th percentile of the sample. The lower and upper lines of the box are the 25th and 75th percentiles, representing the lower and upper quartile, respectively. Data are considered outliers if they are located 1.5 times the interquartile range away from the top or bottom of the box. Figures 2-4 present measurements and calculated values for surface temperatures at the SW wall of the canyon, the NE wall of the canyon and at ground level, for 10:00LT in the morning -13:00LT at noon and 16:00LT in the afternoon, as representative hours for the experimental period.

In the same box plots two different calculated values depicted. The albedo of a smooth concrete asphalt grey slab is close to 0.36 and in walls painted with grey plaster does not exceed the value of 0.4 (Taha et al., 1992), so for the CDF simulations the albedo of the canyons' initial surfaces coating considered equal to 0.3 and for the case of the "cool" coating equal to 0.6 (Figures 2-4). For all calculations the emissivity of the canyons' materials was considered equal to 0.9.

According the plots in the morning the surface temperature on the sunny NE wall is almost 5^0C higher than the opposite SW wall and the grounds' surface temperature is close to 29^0C (Figure 2). At noon (13:00LT) grounds' average surface temperature approaches 41^0C, close to 10^0C higher than the corresponding walls surface temperature (Figure 3). In the afternoon (16:00LT) average surface temperature on the SW wall reaches 35^0C, while grounds' corresponding surface temperature is 4^0C lower (Figure 4). The average calculated values (for albedo equal to 0.3) were very close to average values of measurements. Differences between average measurements and calculated values did not exceed 0.3^0C strengthen the value of the CFD tool used. The measured mean values of surface temperature were always least high than the temperatures calculated for albedo equal to 0.3, which was chosen based the literature, as an appropriate value for the CFD simulations. The reason is that after the years the albedo of coatings decreases and the real value can be measured close to 0.2. In the second task of our study the use of a "cool" coating with higher albedo (equal to 0.6) decreased average calculated values of surface temperature. Almost for all cases after the use of a "cool" material can lead surface temperature 2^0C lower at canyons' walls and 3^0C lower at ground level (Figures 2-4). This conclusion is strongly linked with the angle of elevation of the sun; the thermal properties of the canyons' materials and the geometry of the experimental site.

Air temperature calculated values followed the vertical stratification of the measured ones, during experimental period (Table 1). The range of air temperature differences, between measured and calculated values (for materials with albedo value equal to 0.6), was up to 0.9^0C. These differences depended from the distance from ground level and the time period. This conclusion provided evidences that the increase of materials' albedo can lead to reduction of ambient temperature inside the canyon.

The wind flow as expected cannot be influenced by the change of the surfaces' material (Table 2) since calculated values derived from the CFD simulations did not differ from measurements.

5. CONCLUSIONS

The alternative way to fight heat island in dense urban cities is to increase urban albedo. Difficult is to reconstruct cities, with huge green areas and lower building factor, so in the effort to decrease air temperature in the center of cities scientists focus nowadays in optimization for the reflectivity of the pavements, roofs and walls.

It was proved that an increase on the albedo of a coating in surfaces of a deep street canyon can lead to 3^0C decrease of surface temperature on ground level. The decrease on walls' surface temperature may reach 2^0C. All these conclusions are strongly related to the geometry of the canyon and the solar incidence angle. Ambient air temperature inside the canyon, strongly depending from canyons' covering, may decrease close to 1^0C. Advanced reflective materials for roof and pavements, the "cool materials", are strongly considered as the solution in the fight of the heat island effect (Akbari et al., 2009; Santamouris et al., 2012). Materials "cool" colored painted can contribute to the decrease of surface temperatures and energy consumption in urban areas (Synnefa et al, 2007).

The conclusions of this study are valid for the specific boundary conditions, strongly related to the micro-climatic conditions of the studied area. In the forthcoming study, the t-test of the difference of the means will be applied, in order to prove the goodness of fit between the measurements derived from the extended experimental campaign and the ones raised from the application of the theoretical model. This test will be performed for all measured data and not only for selected hours.

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FIGURES

Figure 1: Mobile Meteorological Station of the University of Athens

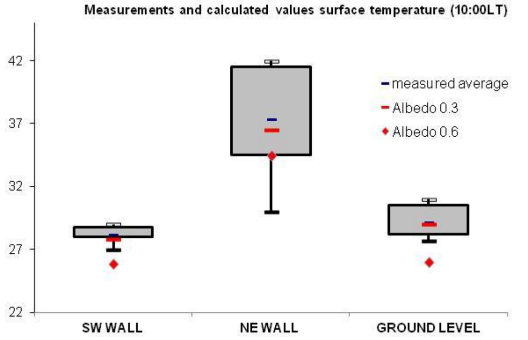

Figure 2: Measured and calculated values at 10:00LT

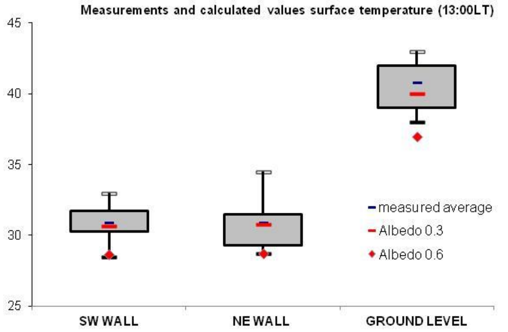

Figure 3: Measured and calculated values at 13:00LT

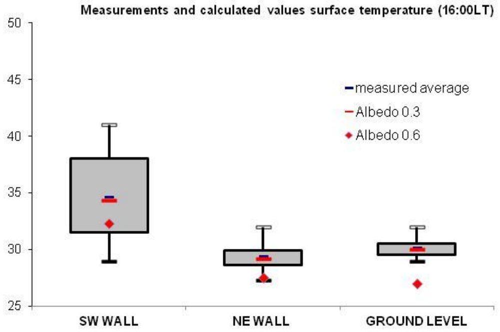

Figure 4: Measured and calculated values at 16:00LT

Table 1 Measurements and calculated values for air temperature inside the canyon

HEIGHT LEVEL	**2 m**	**5.5m**	**9.5m**	**15.5m**
Measurements 10:00LT	26.9	25.9	26.1	26.2
Calculated vales (albedo 0.3)	27.5	26.3	26.5	26.2
Calculated vales (albedo 0.6)	27.3	25.9	25.9	25.7
Measurements 13:00LT	29.5	28.7	28.8	28.8
Calculated vales	29.6	29.0	29.0	28.5

(albedo 0.3)				
Calculated vales (albedo 0.6)	29.0	28.5	28.3	28.0
Measurements 16:00LT	29.0	29.0	29.3	29.2
Calculated vales (albedo 0.3)	29.5	29.0	29.3	29.2
Calculated vales (albedo 0.6)	28.9	28.5	28.4	28.5

Table 2 Measurements and calculated values for wind speed inside the canyon

HEIGHT LEVEL	**2 m**	**5.5m**	**9.5m**	**15.5m**
Measurements 13:00LT	0.33	0.28	0.65	1.16
Calculated vales (albedo 0.3)	0.31	0.27	0.58	1.20
Calculated vales (albedo 0.6)	0.30	0.26	0.59	1.22
Measurements 16:00LT	0.30	0.38	0.35	0.18
Calculated vales (albedo 0.3)	0.32	0.39	0.34	0.23
Calculated vales (albedo 0.6)	0.30	0.35	0.40	0.50