Effect of Materials on the Urban Thermal Environment - A CFD Simulation Approach

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ABSTRACT: Use of high albedo materials reduces the amount of solar radiation absorbed through building envelops and urban structures and thus keeping their surfaces cooler. The cooling energy savings by using high albedo materials have been well documented. Higher surface temperatures add to increasing the ambient temperature as convection intensity is higher. Such temperature increase has significant impacts on the air conditioning energy utilization in hot climates. This study makes use of a parametric approach by varying the temperature of building facades to represent commonly used materials and hence analyzing its effect on the air temperature through a series of CFD (Computational Fluid Dynamics) simulations. A part of the existing CBD (Central Business District) area of Singapore was selected for the study. Series of CFD simulations have been carried out using the software CFX-5.6. Wind tunnel experiments were also conducted for validation. It was found that at low wind speeds, the effect of materials on the air temperature was significant and the temperature at the middle of a narrow canyon increased up to 2.52°C with the façade material having lowest albedo.

Conference topic: 4 Energy and urban planning
Keywords: CBD area, Materials, surface temperature, CFD Simulations, wind speed

1. INTRODUCTION

As a consequence of increasing urbanization and changes in the heat balance, air temperatures in densely built urban areas are higher than the temperatures of surrounding country and this leads to the phenomenon called urban heat island effect. It is well accepted that urban heat island leads to a very high increase in energy use [1, 2, 3]. As reported for US cities with populations larger than 100,000, the peak electricity load will increase by 2.7% to 3.6% for every 1°C rise in temperature [4]. An extensive field measurement conducted recently in Singapore showed a temperature difference of 4.5°C between the CBD (Central Business District) area and the vegetated areas [5]. Use of high albedo materials reduces the amount of solar radiation absorbed through building envelops and urban structures and thus keeping their surfaces cooler. The cooling energy savings by using high albedo materials have been well documented [6, 7]. The orientation of the streets, the H/W ratio, together with the type of material used, defines the surface temperature of the materials. Although the impact of solar reflectivity and the material's emissivity are important, it is important to note that the temperature of a material is determined by its thermal balance, with conductive and convective phenomena taken into account [8].

Higher surface temperatures add to increasing the ambient temperature, as convection intensity is higher. Such temperature increase has significant impacts on the air conditioning energy utilization in hot climates. Many of the previous works in this area were based on simple parametric models and hence the results obtained could not be directly applied to real problems. Hence the main objective of this study is to investigate the microclimatic conditions of the CBD area and to identify the effect of different commonly used façade materials on the air temperature by conducting a series of CFD (Computational fluid dynamics) simulations.

2. METHODOLOGY

A part of the existing CBD area was selected for the study. A series of CFD simulations have been carried out by varying the materials of the building facades to investigate the effect of these on the temperature patterns within the canyons. Boundary condition data has been obtained from the weather data as well as the field measurement. EDSL- Tas building designer software was also used in order to obtain the surface temperature of each of the material.

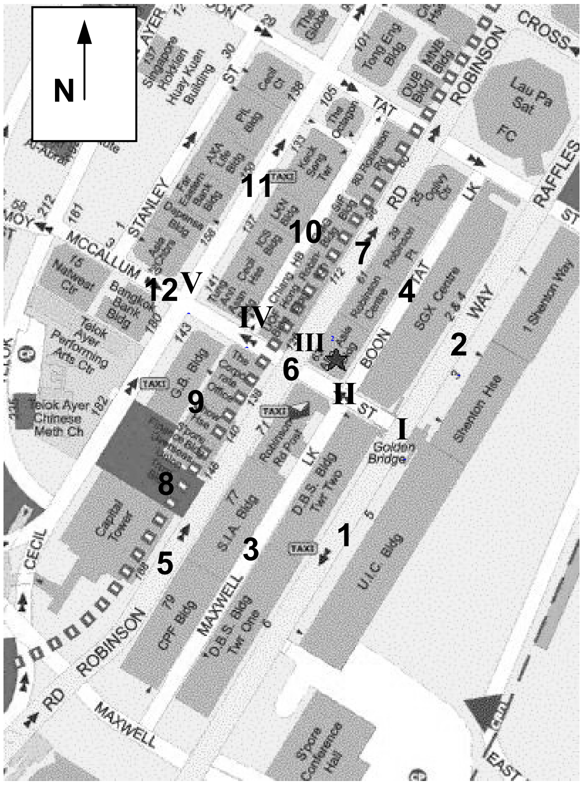

Figure 1: CBD area under study

2.1 The CBD Area

The CBD area under investigation covers a region of 600m X 400m (Figure 1). The area consists of densely populated high rise buildings and deep street canyons. Canyons are numbered from I to IV and measurement locations are numbered from 1 to 12. Table 1 shows the dimension of the canyons. All the 4 canyons under study were asymmetric with varying building heights on the two sides. The width of the road (W) comprise two side walks and other set backs.

Table 1: Dimension of the canyons

No	Locations	Average height of lower continuous canyons (H)	Width (W)	H/W ratio	Max /Min ht of high rise towers(m)
I	1,2	19	30	0.63	180/128
II	3,4	21	14	1.5	180/76
III	5,6,7	21	24	0.88	170/44
IV	9, 10	20	10	2	88/44
V	11	20	30	0.66	90/46

The vicinity can be mainly divided into two; the lower area up to height of 24m consisting of continuous canyons, and the higher area which has high rise building towers up to a maximum height of 250m located randomly above the continuous canyons. Figure 2 shows the physical model of the CBD area, which has been tested in the wind tunnel. The large size as well as the diversified building geometry makes the model very complex for simulation and analysis.

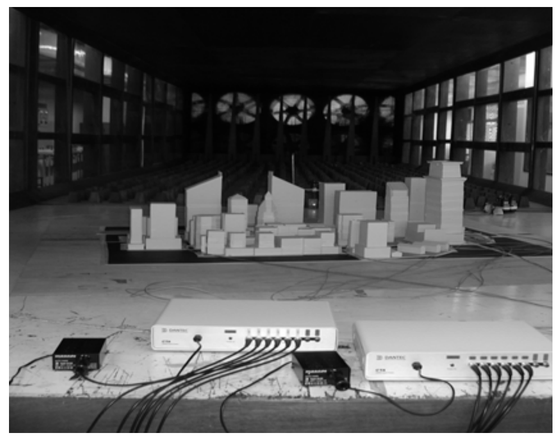

Figure 2: Model used for wind tunnel experiment

As shown in Figure 1, twelve numbers of locations were identified for the analysis. Point 1 and 2 were situated in canyon I. Points 3 and 4 were situated in a relatively narrower canyon II. Points 5, 6 and 7 were situated in canyon III in which Point 5 was just in front of capital tower which is the tallest building in the study area and point 6 was situated at an intersection. Point 8 was not situated within the street, but in an open green area next to the capital tower. Points 9 and 10 were situated in a narrow lane (canyon IV) of 10m wide which is mainly used as access for vehicles to the car park. Point 11 is situated in canyon IV and did not have many high rise buildings on the two sides. Point 12 is situated in canyon which is perpendicular to the canyons under investigation.

2.2 Numerical Simulation Model

The numerical simulation was based on the two equation *k-ε* model using the software CFX 5.6. The steady state flow has been solved using the basic transport equations for continuity, momentum and energy as shown below. Figure 3 shows the geometry of the model in CFX. The area has a dimension of 600m (L) and 400m (W).Since the urban environment is too complex and dynamic being influenced by several parameters, simplifications and assumptions were adopted to form a steady state computational model to predict the microclimatic conditions. The model had a total number of 1.8 million mesh elements.

Transport equations of the k-ε turbulence model:

Continuity: $$\frac{\partial \overline{U}_i}{\partial X_i} = 0$$

Momentum:

$$\overline{U}_j \frac{\partial \overline{U}_j}{\partial X_j} = -\frac{1}{\rho}\frac{\partial \Pi}{\partial X_i} + \frac{\partial}{\partial X_j}\left[(\nu+\nu_t)\left(\frac{\partial \overline{U}_j}{\partial X_i} + \frac{\partial \overline{U}_i}{\partial X_i}\right)\right] - \beta g_i \overline{\theta}$$

Thermal Energy:

$$\overline{U}_i \frac{\partial \overline{\theta}}{\partial X_i} = \frac{\partial}{\partial X_i}\left(k + \frac{\nu_t}{\sigma\theta}\right)\frac{\partial \overline{\theta}}{\partial X_i} + \overline{q}_\theta$$

Turbulence Kinetic Energy:

$$\overline{U}_j \frac{\partial \overline{k}}{\partial X_j} = \frac{\partial}{\partial X_j}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial \overline{k}}{\partial X_j}\right] + \nu_t\left(\frac{\partial \overline{U}_j}{\partial X_i} + \frac{\partial \overline{U}_i}{\partial X_j}\right)\frac{\partial \overline{U}_i}{\partial X_j} + \beta g_i \frac{\nu_t}{\sigma_\theta}\frac{\partial \overline{\theta}}{\partial X_i} - \overline{\varepsilon}$$

Turbulence dissipation rate:

$$\overline{U}_j \frac{\partial \overline{\varepsilon}}{\partial X_j} = \frac{\partial}{\partial X_j}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \overline{\varepsilon}}{\partial X_j}\right] + \frac{\overline{\varepsilon}}{\overline{k}}\left[C_1 \nu_t\left(\frac{\partial U_j}{\partial X_i} + \frac{\partial U_i}{\partial X_j}\right)\frac{\partial \overline{U}_i}{\partial X_j}\right] - C_2 \frac{\overline{\varepsilon}^2}{\overline{k}} + C_3 \frac{\overline{\varepsilon}}{\overline{k}} \beta g_i \frac{\nu_t}{\sigma_0}\frac{\partial \overline{\theta}}{\partial X_i}$$

Eddy viscosity: $$\nu_t = C_D(\overline{k}^2 / \overline{\varepsilon})$$

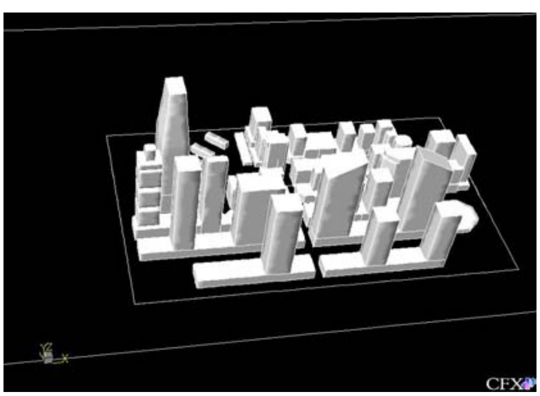

Figure 3: Geometry in CFD

2.3 Boundary Conditions

The airflow was assumed to be parallel to the street axis that means from the S-SW direction which is one of the predominant wind directions in Singapore. The inlet boundary condition was expressed in the form of power law wind profile as explained below to simulate the atmospheric boundary layer. The air temperature was assumed to be 30°C.

Power law:

$$\frac{U}{U_{ref}} = \left(\frac{Z}{Z_{ref}}\right)^a$$

Where, reference height z_{ref} = 10m, coefficient of roughness for city centre a =0.4

The wind speed (u_{ref}) was based on the data obtained from the Singapore Meteorological station over 18 years. The outlet was modeled as free pressure boundary. The surface temperatures of different materials were obtained using Tas building designer software and this has been verified by site measurement using an infra red camera. These surface temperature values ranging from 32ºC to 42ºC were assigned as wall boundary conditions with fixed temperature for the external facades of the buildings. The ground surface was assigned a surface temperature value of 45°C to represent the road which is made of asphalt. The simulations have been conducted for different wind speeds (u_{ref}) ranging from 0.1m/s to 6 m/s.

2.4 Different façade materials

The various materials used consist of different colors of Aluminium, glass as well as concrete which are the commonly used façade materials of the buildings in the CBD area of Singapore. The properties of these materials like solar absorptance, emissivity, conductivity, density and specific heat are used as input in the EDSL- Tas building designer software in order to obtain the surface temperature of each of the material. Table 2 shows the thermal properties of different materials as well as the maximum surface temperatures obtained from Tas simulation. The surface temperatures measured at the site during a hot afternoon showed similar results.

Table 2: Different materials used for the simulation and their surface temperatures

Material	Surface Temperature (°C)	Solar absorptance	Emissivity	Conductivity(W/mC)	Specific heat(J/KgC)
Al (white)	32	0.17	0.22	204	896
Al(golden	36	0.53	0.22	204	896
Al (black)	42	0.96	0.22	204	896
Concrete	38	0.65	0.9	0.1	1094
Clear glass	34	0.11	0.75	1	840

3. RESULTS AND DISCUSSIONS

3.1 Effect of wind speed

The CFD simulations were conducted for different wind speeds in order to find out the critical wind speed at which the effects of materials become crucial. Figure 4 shows the air velocity distribution at a height of 5m in the middle of the canyons for different wind speeds. In this comparison black Aluminium which has the highest surface temperature was used as the façade material. It can be observed that the air velocity at different locations increased with the increase in wind speeds and all the locations other than 10 had maximum air velocity with maximum wind speed of 6m/s. Location 10 is situated in a very narrow street as shown in Figure 1and had higher air velocities for lower wind speeds. The velocities at different locations did not vary significantly for wind speeds 0.1 m/s and 0.5 m/s but increased substantially for 4m/s and 6m/s.

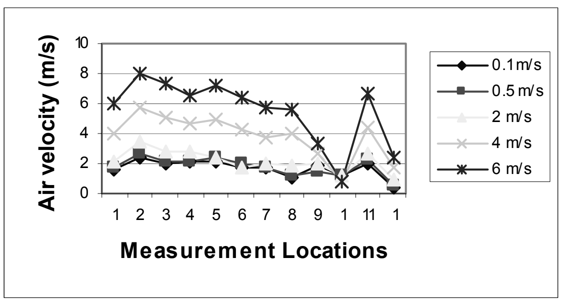

Figure 4: Air velocity within the canyons at different wind speeds.

Figure 5 shows the temperature distribution for different wind speeds. It can be observed that the air temperatures did not vary significantly for higher wind speeds except for location 10. However, the temperature increased significantly when the wind speed was reduced to 0.1m/s. Therefore the wind speed of 0.1m/s which represents almost still air condition has been used as the boundary condition for further simulations in order to compare the thermal effect of different materials. The air temperatures were influenced by the canyon geometry also and locations at very narrow streets (Location 9 and 10) had the highest temperatures. Further analysis at location10 showed that even at 4m/s wind speed the air temperature with black Aluminium as the façade material has been 1°C higher than the same with white Aluminium as the façade material.

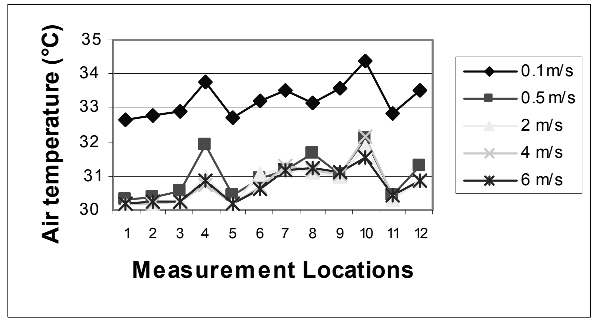

Figure 5: Temperature within the canyons at different wind speeds

Near locations away from the inlet and situated in wider canyons with low H/W ratios, hot air was observed to be moving upwards for the wind speed of 4m/s whereas for lower wind speeds, hot air was moving towards the centre of the canyon from both sides of the facades. Figures 6, 7 and 8 show the temperature contours at location 11 situated at canyon4.

Figure 6: Temperature contours at location11 for black Aluminium at wind speed 4m/s

Figure 7: Temperature contours at location11 for black Aluminium at wind speed 2m/s

Figure 8: Temperature contours at location11 for black Aluminium at wind speed 0.1m/s

At higher areas above the continuous canyons, the effect of façade materials at higher wind speeds was significant only very near to it, but at 0.1m/s wind speed, the top of the canyons had high temperatures all through the entire cross section.

3.2 Effect of different materials

Figure 9 shows the temperatures at different locations using different facade materials at the wind speed of 0.1m/s. As expected, the materials with higher surface temperatures gave rise to higher air temperatures and black Aluminium façade resulted in the highest air temperature inside the canyons. The highest temperature of 34.39°C was obtained at location10. Location4 also had high temperature of 33.75°C.

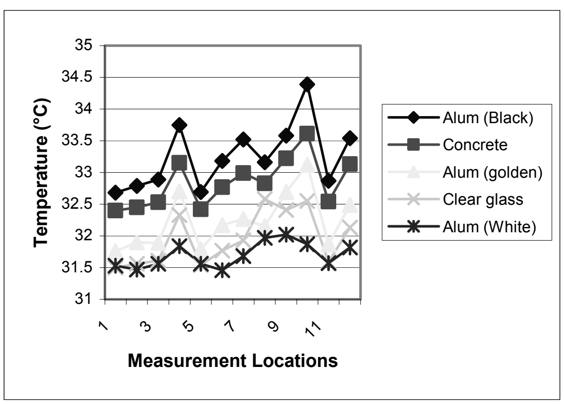

Figure9: Air temperature inside the canyon using different façade materials

When white Aluminium was used as the façade material, temperatures at locations 9 and 10 were reduced by 1.56°C and 2.52°C respectively. The temperature at location 4 was reduced by 1.91°C and the temperature at location 7 was reduced by1.86°C.

Figures 10 and 11 show the temperature contours at location 9 through a vertical section perpendicular to the canyon. The width of this canyon was only 10m. It can be observed that towards the higher area, white Aluminium facade gave rise to uniform temperature throughout the cross section and for black Aluminium, the temperature was very high near the facades and was decreasing towards the centre of the canyon.

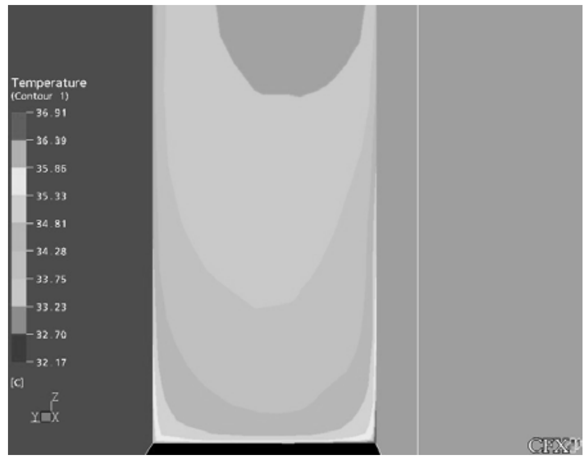

Figure10: Temperature contours for black Aluminium

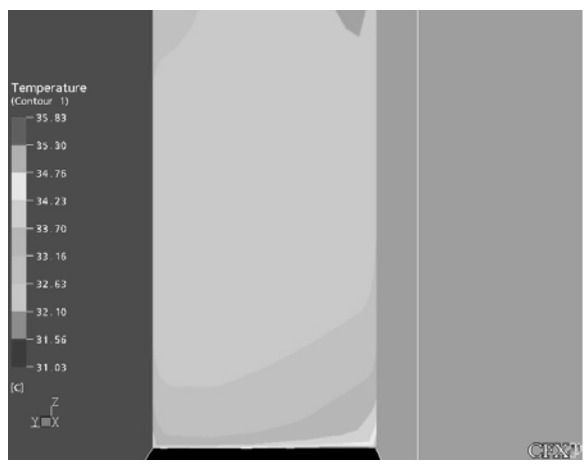

Figure11: Temperature contour for white Aluminium

For black Aluminium, the lower area of the canyon had a temperature ranging from 33.75°C to 34.81°C. At the higher area, the temperatures were in the range of 32.7°C to 33.75°C. When white Aluminium was the façade material, the temperature at the lower area varied from 32.6°C to 33.7°C and the temperature at the higher area varied from 32.1°C to 32.6°C. It is to be noted that the high temperature near the ground is due to the convective effect from the road having high surface temperature.

For wider canyons like canyon I and V the difference in temperature for different façade materials was up to 1.32°C. For canyon III, the difference was up to 1.8°C and for canyon II, the difference was up to 1.91°C. Maximum difference of 2.52°C was observed at canyon IV.

As stated earlier, previous studies had shown that the peak electricity loads will increase by 2.7 % to 3.6 % for every 1°C rise in temperature. Based on this, the increase in temperature inside the canyons with low albedo facade materials can increase the peak electricity load by 6.8% to 9%.

CONCLUSION

The series of CFD simulations have shown that facade materials and especially their colors play a very important role in the formulation of the thermal environment inside urban canyons. At higher wind speeds, the effect of materials on the urban thermal environment was not much significant for wider canyons. However narrow canyons had higher temperature even for higher wind speeds when low albedo materials were used and the temperature in the middle of the canyon was increased by 1°C. At very low wind speeds, the effect of materials was found to be significant and the temperature at the middle of the narrow canyon increased up to 2.52°C with the façade material having lowest albedo. It was noted that the temperature at the middle of the wider canyons also increased up to 1.3°C. The increase in temperature inside the canyons can cause the peak electricity load to increase by up to 6.8% to 9%.

REFERENCES

[1] Agis M. Papadopoulos, the influence of street canyons on the cooling load of buildings and the performance of air conditioning systems., Energy and Buildings vol. 33, pp 601-607, 2001.
[2] Hassid S, Santamouris M, Papinikolaou N, Linardi A, Klitsikas N, Georgakis C, Assimakopoulos D.N, The effect of Athens heat island on air conditioning load, Energy and Buildings 32 (2000) 131-141.
[3] Santamouris M, Papanikolaou N, Livada I, Koronakis I, Georgakis C, Argiriou A, Assimakopoulos D. N, On the impact of urban climate on the energy consumption of buildings, Solar energy, Vol.70, pp.201-216, 2001.
[4] Akbari,H., Davis,S.,Dorsano,S.,Huang,J. and Winett,S. Cooling our Communities-A guidebook on Tree Planting and Light Colored Surfacing (1992). US Environmental Protection Agency. Office of Policy Analysis, Climate change division.
[5] Wong, N H and Y CHEN, Study of Green Areas and Urban Heat Island in a Tropical City. *Habitat International* (IN PRINT).
[6] Akbari. H, Sarah Bretz, Dan M. Kurn and James Hanford, Peak power and cooling energy savings of high-albedo roofs, Energy and Buildings 25 (1997) 117-126.
[7] Taha H, Akbari H, Rosenfeld.A, and Huang J, Residential cooling loads and the urban heat island-the effects of albedo, Building and Environment, Vol 23,No.4, pp 271-283, 1988.
[8] Santamouris M, Energy and climate in the urban built environment, James & James Science Publishers, London, 2001.