Effect of Canyon Geometry on Outdoor Thermal Comfort:
A case-study of high-density, warm-humid climate

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ABSTRACT: A successful urban planning and design solution ought to present a comfortable setting for its pedestrians inside urban canyons, because it is fundamental to encourage a good quality urban life and promote health and wellbeing of humans. Recent findings have demonstrated that microclimate inside urban canyons has substantial influence upon the outdoor thermal comfort at the street level .This study, therefore, intends to devise early stage building and urban design strategies to improve outdoor thermal comfort. For this study, a number of existing urban canyons in Dhaka city have been chosen with a range of geometries combined with a variety of street orientations. The microclimatic characteristics of the canyons are analysed through a high resolution CFD microclimatic model: ENVI-met Version 4. Thermal comfort was evaluated with the PET index with the aid of RayMan1.2. Important findings include that deeper street canyons result in reduced air temperature but increased T_{mrt} thus presenting apparently conflicting design options to achieve outdoor comfort. However, such apparently conflicting findings offer the potential for designers to find a variety of canyon geometries appropriate for a tropical city context.

Keywords: canyon geometry, mean radiant temperature, air temperature, thermal comfort

INTRODUCTION
The thermal environment of urban spaces plays a great role on the quality of life in a city. It directly affects people's behaviour and usage of outdoor spaces and can help to support social, economic and cultural vitality. Comfortable urban spaces can furthermore encourage the use of more sustainable forms of transport – including walking, cycling and public transport nodes. Therefore, a sustainable urban design strategy should give a high priority to the urban microclimate and thermal comfort implications.

The city of Dhaka in Bangladesh is one of the fastest growing mega-cities in the world, receiving over 300,000 to 400,000 new migrants per annum. The deterioration of the urban microclimate due to unplanned construction of built forms, which is largely the outcome of uncontrolled urbanization, is a major concern in Dhaka. The lack of effective urban planning has further worsened the situation. It is becoming increasingly difficult to ignore the unfavourable impact of the urban pattern on city's microclimate. Increased air temperature and reduced vegetation in this urban heat island [1] exacerbated by the climate change scenarios, is directly affecting comfort levels in urban outdoor spaces. In this context, urban planning can play a substantial role to modify the microclimate of city's outdoor spaces. According to previous research [2, 3] it is possible to control the urban microclimate through a careful arrangement of urban blocks. The study intends to find how urban geometry can affect the outdoor thermal environment in a high-density warm humid context.

Outdoor open spaces in urban areas should be considered in relation to the built-form as they complement each other [4]. Therefore, to create a comfortable urban microclimate, a harmonious balance between the built form and open space is necessary. The study is concerned with the quality of urban spaces, particularly streets, adjacent to the buildings. The conditions of these spaces not only affect the social life but their atmospheric conditions will directly influence the energy demands of the nearby buildings. Promoting the idea of designing the city's buildings in relation to the adjoining outdoor spaces will encourage the development of building proposals that simultaneously address the quality of the urban spaces that emerge. Such spaces can foster a vibrant urban social life, accommodating a myriad of activities which will in turn lead to a more sustainable future of cities [5].

URBAN GEOMETRY AND CLIMATE
In a tropical context, the primary challenge in designing a thermally responsive street is to achieve shelter from excessive solar gain, because of higher solar angles. Shading has been identified as the main strategy to promote comfort conditions in the warm climates [6]. Givoni [7] has also emphasised the benefits of lowering solar and long-wave radiation as the principal strategy to achieve a cooler ambience in outdoor spaces. Inside an urban canyon (UC), the surface temperatures of the flanking buildings, the sensible heat flux transferred to air

from building surfaces and consequently the air temperature (Ta) is significantly affected by the presence or absence of direct solar radiation [3,8, 9].

It is important to note that air temperature inside the UC will vary temporarily but spatial difference is generally insignificant. Nakamura and Oke [8, 10] found that at any particular time, air temperature does not vary radically (usually less than 1^0C) across the height of the same UC with an aspect ratio (H/W, average building height to street width) of 1. Therefore thermal comfort studies explicitly depending on air temperature are inadequate as ascertained by Jendritzky and Nuber (1981) [cited in 11, p48] especially in the outdoor context where mean radiant temperature (T_{mrt}) can be significantly different from air-temperature. Tmrt is identified as the most influential factor to determine comfort levels in outdoor thermal environments[12,13, 14]. Under direct solar radiation, the difference between T_{mrt} and T_a could be more than 30^0C, whereas, for shaded areas a difference of 5^0C has been reported [9].T_{mrt} is twice as important as DBT in the case of tropical climates, whereas in cooler climates the impact of DBT and T_{mrt} are similar [15]. In warm climates:

Environmental Temperature (EnvT)= 2/3T_{mrt}+1/3 DBT

Therefore, a key strategy to enhance outdoor comfort should first aim to lower the amount of direct, diffused and reflected radiation. Lowering air-temperature and enhancing wind speed should be lower priorities as they are less affected and controlled by urban geometry. Tmrt is the average temperature of the surrounding surfaces acting upon a standing person that represents its radiant heat exchange with the environment [16]. In this study, T_{mrt} is calculated by ENVI-met using the following formula [17]:

$$T_{mrt} = \left[\frac{1}{\sigma_B}\left(E_t(z) + \frac{\alpha_k}{\varepsilon_p}\left(D_t(z) + I_t(z)\right)\right)\right]^{0.25}$$

The calculation includes all radiation fluxes, i.e. direct irradiance $I_t(z)$, diffuse and diffusely-reflected solar radiation $D_t(z)$ as well as the total long-wave radiation fluxes $E_t(z)$ from the atmosphere, ground and walls.

Another important parameter that determines the canyon microclimate is Sky View Factor or SVF, described as the proportion of visible local sky not obstructed by buildings. It ranges from 1 (free sky) to 0(no sky visible). Inside a canyon, the SVF is inversely proportional to the H/W ratio. In a high-density urban area with a H/W ratio of 4 or more, the amount of radiation reaching the ground is smaller in comparison to medium density areas (H/W ratio of 1), as it is mainly absorbed high above the ground level [16]. Therefore, daytime air temperature increases with decreasing H/W ratio and larger view of the sky (SVF) [16, 18]. This phenomenon is mainly applicable to mid-latitude cities. In the case of equatorial climates the effect is rather reduced due to high solar altitude [19]. Despite the fact that deep canyons are able to cut a large amount of direct solar radiation, it may on the other hand assist in entrapping the reflected short and long-wave radiation and reducing wind-driven cooling [20].

STUDY AREA

Dhaka is located at 23.24°N, 90.23°E which falls under tropical Monsoon climate with a distinct warm-humid rainy season, a hot-dry summer and a short cool-dry or winter season. In outdoor spaces in Dhaka we see a preference for shaded spaces and exposure to air flow [21].Further studies [22] show that in tropical climates like Dhaka under still air conditions for people wearing typical summer clothes (.4 to .5 Clo) and being involved in sedentary activities, the comfortable temperature ranges from 28.5^0C to 32^0 C at an average relative humidity of 70%.

Two different case study areas with different land-use patterns have been chosen for this study, located in Baridhara and Sukrabad (Fig.1). Baridhara is a medium-density formal residential area with mostly uniform building heights (6 stories) and a regular street pattern, while Sukrabad is a traditional mixed-use residential area with a combination of different building heights and plot sizes.

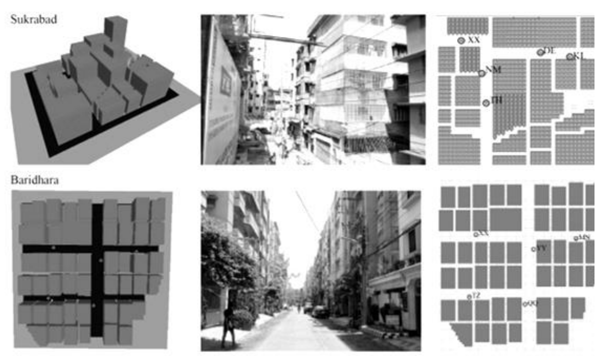

Figure 1:Case-study area and measurement points

METHODOLOGY

In this paper, the pedestrian thermal environment (at a height of 1.5 m) has been calculated and compared for the two case-study areas with the aid of ENVI-met Version 4. The climatic parameters include: air (T_a), radiant (T_{mrt}) and surface (T_s) temperature along with direct, reflected short-wave and long-wave radiation. Unlike the previous version (3.1), the latest version of ENVI-met is able to consider the heat capacity of the walls in the calculations [23]. As cloud coverage and its temporal variation is complex, a clear sky condition is assumed for all model situations. Air temperature and relative humidity was 'forced' in the simulation with the data collected from a local weather station. The input data for other parameters are shown in Table 1.

Date of start of simulation	10 Aug 2012
Time of start of simulation	7:00 am
Simulation period	18 hours
Wind speed at 10 m height (m/s)	1.3
Wind direction	135
Roughness length	0.01
Initial air temperature (°C)	30.15^0C
Specific humidity at 2500 m (g/kg)	14
Relative humidity at 2 m height (%)	71

Table 1: Input data for simulation

The building material was considered the same for all buildings for ease of comparison. The simulation was carried out for a typical day during the hot-humid season, in mid-August when a high air temperature is coupled with high relative humidity and creates a challenging comfort environment [22].Thermal comfort was assessed by Rayman. The simulated climatic data calculated by ENVI-met was used as an input for PET calculations in Rayman, which included air temperature, wind speed and direction, relative humidity and mean radiant temperature.

RESULTS AND FINDINGS

Air Temperature: Figures 2(a) and (b)shows the air temperatures in the two different sites. Higher temperatures are observed in Baridhara which is the regular planned residential area in comparison to Sukrabad, an organic and irregular residential area. In the case of N-S streets the temperature difference between the sites is almost 2^0C, whereas in E-W streets the difference is around 1^0C. The temperature difference between the different sites is not insignificant even when the input data (collected from the local weather stations) is assumed to be the same for all simulations at different sites. Ali-Toudert and Mayer [24] also reported similar variations between deep and shallow canyons. In reality the input data may be different due to different building materials, vegetation and other parameters. In the simulation models, buildings were simplified and material was kept the same in order to understand the relative impact of canyon geometry rather than understanding the effect of facade properties. Even a modest reduction in outdoor air temperature has implications on the building energy performance. For instance, Chen and Wong [25] and Wong et al [26] have reported a 5% saving in building energy consumption resulting just from 1^0C reduction in outdoor air temperature.

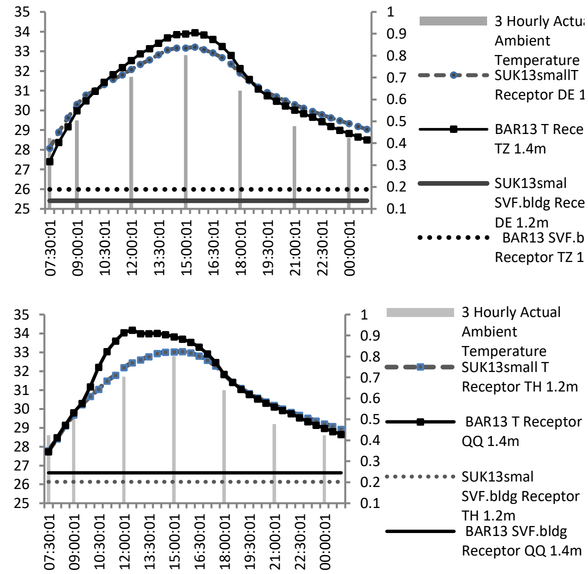

Figure 2: Comparison of Air Temp in Residential in E-W (a) and N-S(b) Street Canyons between Baridhara and Sukrabad

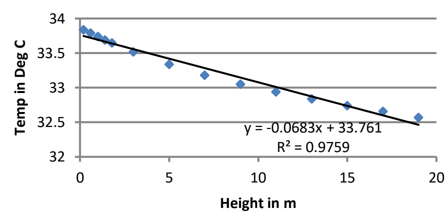

Figure 3:Temperature decreasing with height due to lapse rate

Within the same canyon the temperature may also vary. Figure3 shows that air temperature decreases slightly (1.5^0C) with height between the canyon ground surface (0.2m) and the roof (20 m). However, the correlation between air-temperature and SVF is clear from all the data showing that air temperature decreases in deeper canyons with lower SVF and increasing H/W ratio. Both case study areas show higher air-temperatures than the ambient temperature.

*Mean Radiant Temperature:*Comparing the results in Figures 4 and 5, it is clear that T_{mrt} is largely controlled by the amount of direct short-wave radiation and the presence of shade [12]. In Fig. 4, the T_{mrt} of sunlit areas in N-S street at 14:00pm (the hottest time of the day) in Baridhara is 35^0C higher than shaded parts.Findings from others [13] also indicate similar differences in Colombo. Fig. 4 also indicates that N-S streets in Baridhara have lower T_{mrt} than E-W streets.The impact of orientation is also visible in Sukrabad. In both sites, the spaces in between buildings which are constantly in shade are much cooler in comparison to the streets where H/W ratio is lower and SVF is higher, as one would expect. It indicates the importance of shade to lower the mean radiant temperature which ultimately results in improved outdoor thermal comfort during the daytime. Throughout the night, T_{mrt} drops by about 10^0C and air-temperature by around 5^0C in N-S canyon in Sukrabad between 6 pm and 6 am,even though the SVF is very low(0.202). Therefore, any strategy to lower the T_{mrt} should focus on daytime strategies like maximising shading [12].

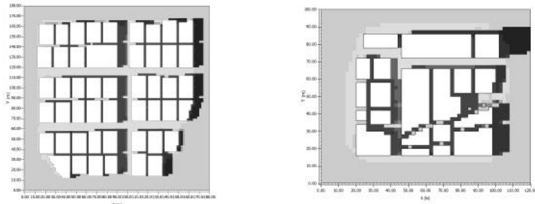

Figure 4: Comparison of MRT in Sukrabad and Baridharain N-S and E-W oriented streets

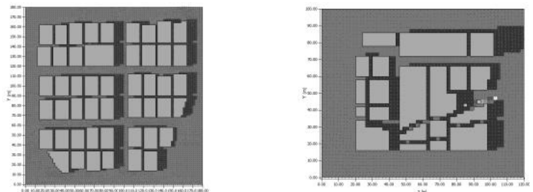

Figure 5: Comparison of Short-wave radiation at 14pm in Sukrabad and Baridharain N-S and E-W oriented streets

Tmrt, however, is not governed by the presence of shade only. The ground surface temperature and longwave heat fluxes from building facades cannot escape easily due to restricted SVF. Inside deeper UCs mutual reflection and absorption of radiation tend to increase resulting in a lower albedo. Therefore, deeper canyons have higher day-time pick value of net radiation in comparison to shallower canyons [19,20].

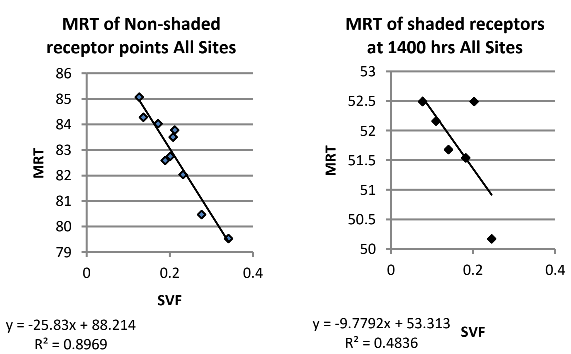

Figure 6: Comparison of SVF and MRT at 14pm in Sukrabad, and Baridharain in N-S and E-W oriented streets

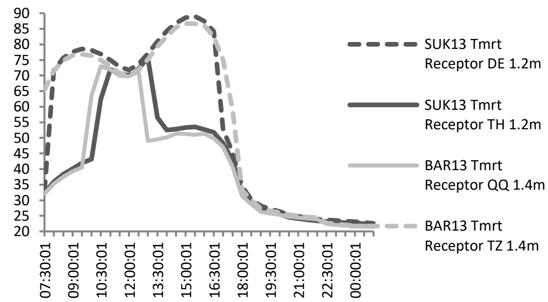

Figure 7: Comparison of MRT in Sukrabad and Baridhara

Fig.6 indicates this strong corelation between SVF and Tmrt. Fig. 7 also shows that the Tmrt for deeper canyons in Sukrabad area in both N-S and E-W orientations is atleast 2^0C higher than shallower canyons in Baridhara. Moreover, shade plays an important role in measuring Tmrt. Therefore, a shaded area although located in a wider canyon can have a lower Tmrt in comparison to a sunlit area in a deeper canyon.

Surface Temperature: Figure 8 suggests that the ground surface temperature is almost 2^0C higher in the deeper canyon in Sukrabad (irregular array) in comparison to Baridhara (regular array). The increased surface temperature causes higher T_{mrt} (2^0C difference) in the deeper canyons.

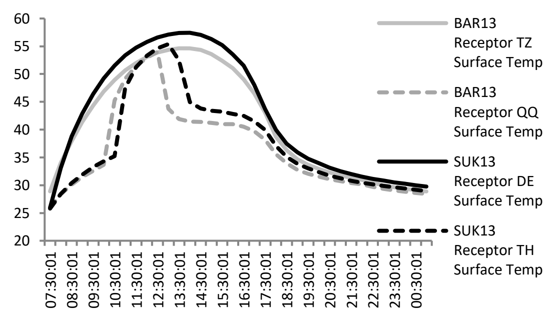

Figure 8: Surface temperature in Sukrabad and Baridhara

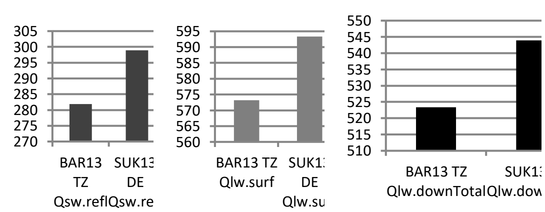

Figure 9: Comparison of Qsw.refl ,Qlw.surf and Qlw.downTotal between deeper (SUK13 DE) and shallower (Bar13 TZ) canyon

From Figures 9(a), (b) and (c) it is apparent that the amount of reflected short-wave radiation($Q_{sw.refl}$),long-wave emission of surface ($Q_{lw.surf}$) and absorbed long-wave radiation from environment reaching the ground

($Q_{lw.downTotal}$)vary between deeper and shallower canyons. Inside deeper canyons, $Q_{sw.refl}$ and $Q_{lw.downTotal}$ from environment (sky, building and vegetation) is higher. Therefore the $Q_{lw.surf}$ in deeper canyon is also higher. This suggests a day-time urban heat-island effect in deeper canyons.

PET Assessment: Figure 10 suggest that PET is mainly controlled by the presence of shade. At the hottest time of the day, PET values in the sun-lit areas inside urban canyons exceed 58^{0}C, indicating a very uncomfortable ambience, while for the shaded areas the value is around 40^{0}C. Similar PET values during peak hours were also reported in previous studies [24].PET values in the shaded areas are almost 20^{0}C less which reveals the significance of shade. The impact of orientation and SVF upon PET is not clear in the figure as sun is very high at this time of the day in this location. Figure 11 denotes a rather weak correlation between SVF and decrease in PET value, due to high solar altitude at this hour.

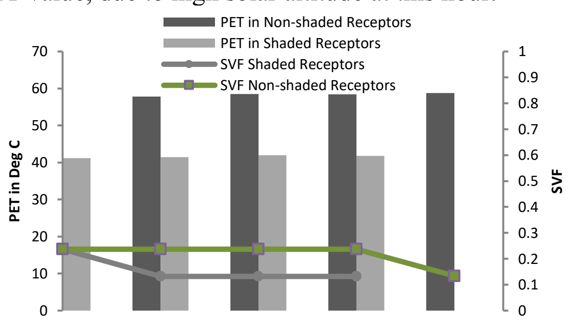

Figure 10: Comparison of PET value at 14:00 hours in shaded or non-shaded areas in Baridhara and Sukrabad

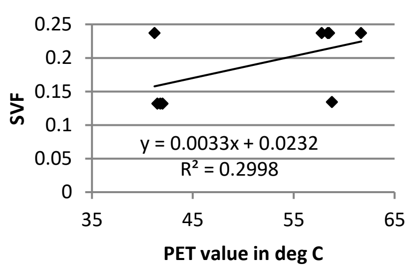

Figure 11: SVF measured in Townscope(2012) for input in Rayman

CONCLUSIONS

The key findings from this research can be summarised as follows:

- In a deeper canyon daytime air temperatures are lower due to a restricted SVF, although the reduction is not very significant (less than 2^{0}C). However, after sun-set, deeper canyons are found to be little warmer than shallower canyons.
- No significant relation is found between air temperature and canyon orientation.
- All urban canyons show higher temperatures in comparison to ambient air-temperature over an 18 hour cycle, due to higher thermal storage and elevated long-wave emission from the building mass in urban areas.
- The presence of direct solar radiation is the main factor influencing T_{mrt} and therefore thermal comfort. The study suggests a difference of 35^{0}C in T_{mrt} values between shaded and sun-lit areas. During the hottest time of the day at 3pm, T_{mrt} is at least 50^{0}C higher for sun-lit areas and 20^{0}C higher for shaded areas in comparison to the air-temperature.
- T_{mrt} is largely affected by orientation as orientation governs the presence of shade inside urban canyons. North-South canyons in the study areas were found to be more comfortable in comparison to West-East canyons.
- The results show higher T_{mrt} in deeper canyons comparing different measurement points in different canyons with varying SVF values in the presence of shade. Matching correlations are found when comparing all receptor points in the sun-lit area. This is due to the increase of net radiation inside deeper canyons, as confirmed in previous research [19, 20].

It is important to note that impact of shade and the influence of H/W ratios have to be considered separately to understand the resulting T_{mrt}. Several studies [6, 9, 12] have associated the reduction of T_{mrt} with reducing SVF or increasing H/W ratio, while this study suggests that the relation should refer to the presence or absence of shade. Increased H/W ratio can increase the mutual shading inside urban canyons and greater shade can reduce T_{mrt} when compared with T_{mrt} of sun-lit areas. It may be possible to achieve greater shade with a higher H/W ratio due to a reduction of direct solar radiation at street level. However, greater street canyon depth results in higher reflection of diffused short-wave radiation and trapping of long-wave radiation from the building mass, especially in a high density context.

Increasing building height, thereby increasing density, could be a strategy to increase mutual shading between buildings in order to achieve lower T_{mrt} at street level. It could prove valuable for the mid-latitude cities even during the hottest time of the day when a large amount of direct radiation can be avoided by introducing deep canyons. However, it has to be remembered that solar altitude is already very high in this location during the midday so that even deep canyons may not be able to avoid sunlight penetration. Furthermore, increasing density in this way results in a larger gain in net radiation which will increase T_{mrt} even in the presence of shade.

The present density in Dhaka is already very high, especially in terms of land-coverage in the informal areas. Even, in planned formal residential areas like Baridhara, the FAR value is approximately 3.1 and the percentage of land coverage is 61% - both are very high. Although modern urban planning intends to promote high-density and compact development to achieve sustainability, it does not discuss the consequences or upper limits of high-density. Therefore, it is important to explore the implications of high density with the provision for increasing SVF which could provide sufficient density without impairing the street thermal comfort. Previous research [27] has shown that it is possible to produce high density and high SVF, as a result of a diverse urban geometry (i.e. variations in building heights and in spacing results in quite high densities and quite high SVFs compared to a traditional, more regular urban form). To conclude, the results and information from the current study can be integrated in the future urban planning processes.

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