IMPACT OF CANYON GEOMETRY UPON URBAN MICROCLIMATE: A CASE-STUDY OF HIGH-DENSITY, WARM-HUMID CLIMATE

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ABSTRACT

Recent findings have demonstrated that microclimate inside urban canyons is largely controlled by its geometry. This study, intends to examine the impact of canyon geometry upon air and radiant temperature in a high density warm humid context. For this study, two urban canyons in Dhaka city have been chosen with different street orientations. The microclimatic characteristic was observed through a high resolution CFD microclimatic model: ENVI-met Version 4. Important findings include reduced air temperature but increased Tmrt in deeper canyons while presenting apparently conflicting design options to achieve comfortable urban-microclimate. However, there are potentials to find a variety of canyon geometries that are harmonious with the apparently conflicting design objectives in a tropical city context.

Keywords: canyon geometry, sky view factor, height/width ratio, mean radiant temperature, air temperature

INTRODUCTION

Unbridled urbanisation in Dhaka has led to growth of disorganised and unplanned arrangement of built forms. Lack of effective urban planning has further worsened the situation. It is becoming increasingly difficult to ignore the unfavourable impact of urban pattern on city's micro-climate. Increased air temperature and reduced vegetation in this urban heat island 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 [1] 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. 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 adjacent to the buildings. This mainly includes pedestrian streets. These spaces not only affect the social life of the surrounding buildings but also comfortable atmospheric conditions in these areas will directly reduce the energy demand of the buildings. Promoting the idea of designing the city's outdoor spaces in relation to the neighbouring buildings will encourage the concept of city design and urban planning simultaneously with the design of urban spaces. The spaces will assist in vibrant social life in cities as well as accommodating myriads of activities which will in turn lead to a sustainable future of cities.

URBAN GEOMETRY AND CLIMATE

The main difficulty in designing a thermally responsive street is to achieve shelter from excessive solar gain, specially in a tropical context where the sun is very high in the sky most around the year. Shading has been identified as the main strategy to promote comfort conditions in the warm climates [2]. Givoni [3] has also emphasised on the benefits of lowering solar and long-wave radiation to be the primary strategy to achieve 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 consecutively the air temperature (Ta) is significantly affected by the presence or absence of direct solar radiation [1,4].

It is important to notice that air temperature inside the UC will vary temporarily but spatial difference is generally insignificant [4].Therefore thermal comfort studies explicitly depending on air temperature are imprecise as ascertained by Jendritzky and Nuber (1981) [cited in 5, p 48] specially in the outdoor context where mean radiant temperature (Tmrt) can be significantly different from air-temperature. Tmrt is identified as the most influencing factor to determine comfort level in outdoor thermal environment [6,7]. In fact, Tmrt is twice as important as Ta in case of tropical climates, whereas in cooler climates the impact of Ta and Tmrt are similar [8]. Therefore, the main strategy to enhance outdoor comfort should first aim to lower the amount of direct, diffused and reflected radiation. Tmrt is the average temperature of surrounding surfaces acting upon a standing person that represents its radiant heat exchange with the environment.In this study, Tmrt is calculated by ENVImet using the following formula [9]:

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

Tmrt calculation includes all radiation fluxes, i.e. direct irradiance It(z), diffuse and diffusely-reflected solar radiation Dt(z) as well as the total long-wave radiation fluxes Et{z} from the atmosphere, ground and walls.

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 = 1), as it is mainly absorbed high above the ground level [cited in 10]. Therefore, daytime air temperature increases with decreasing H/W ratio and larger view of the sky (SVF, Sky View Factor) [10]. This phenomenon is mainly applicable to mid-latitude cities. In case of equatorial climate the trend is rather reduced due to high solar altitude [11]. Despite the fact that deep canyons are able to cut 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 [12].

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 the outdoor spaces in Dhaka we see a preference for shaded spaces and exposure to air flow. 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 storied), while Sukrabad is an informal mixed-use residential area with a combination of different building heights and plot sizes.

METHODOLOGY

In this paper, the pedestrian level (1.5 m) thermal environment has been calculated and compared for two case-study areas with the aid of ENVImet Version 4. The climatic parameters include: air (Ta), radiant (Tmrt) and surface (Ts) temperature along with direct, reflected short-wave and long-wave radiation. Unlike the previous version (3.1), the latest version of ENVImet is able to consider heat capacity of the walls into calculations [13]. 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 local weather station. The input data for other parameters are shown in the Table. The building material was considered same for all buildings for easy comparison. The simulation was carried out for a typical day during the hot-humid season, in the mid-August when a high range of air temperature is coupled with high relative humidity and creates an uncomfortable environment.

Date of start of simulation	10 Aug 12
Time of start of simulation	7:00 am
Simulation period	18 hours
Wind speed at 10 m height	1.3(m/s)
Wind direction	135
Roughness length	0.01
Initial air temperature	30.15^{0}C
Specific humidity at 2500 m	14 (g/kg)
Relative humidity at 2 m	71(%)

Table 1: Input data for simulation

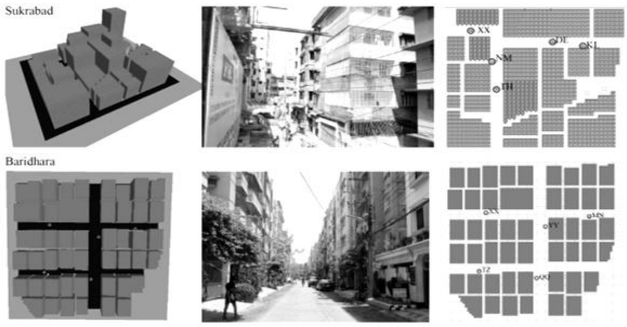

Figure 1:Case-study area and measurement points

RESULTS AND FINDINGS

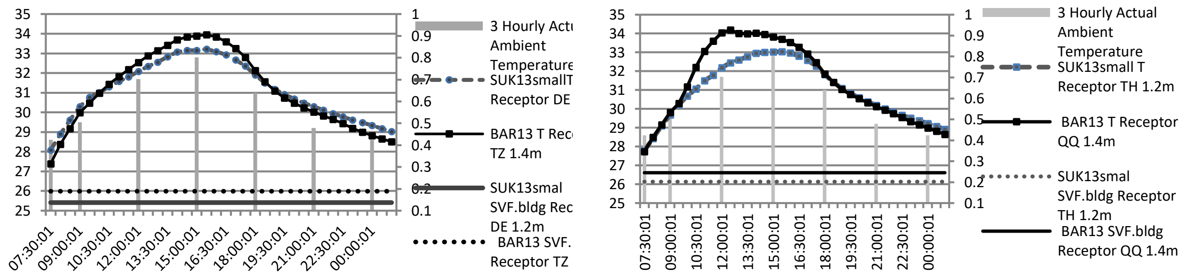

Figure 2: Comparison of Air Temp in Residential in E-W (a) and N-S(b) Street Canyons between Baridhara-DOHS and Sukrabad

Fig.2 (a) and (b) represents the relation between SVF and air temperature in two different sites. Higher temperature is observed in Baridhara DOHS which is a planned residential area in comparison to Sukrabad, an informal residential area. In case of N-S streets the temperature difference between the sites are almost 2^{0}C, whereas in E-W streets the difference is around 1^{0}C.

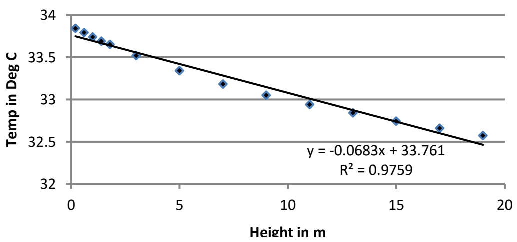

Figure 3: Temperature decreasing with height due to lapse rate

The temperature difference between different sites in Dhaka is not insignificant (2^{0}C) although the input data (collected from the local weather stations) was same for all simulations at different sites. In actual field the input data may be different due to different building materials, detail ground surface pattern and other complex parameters. Even a smaller reduction in outdoor air temperature has its implications on the building energy performance. For instance, Wong et al [14] have reported a 5% saving in building energy consumption resulted from 1^{0}C reduction in outdoor air-temperature. Within the same canyon the temperature may also vary. Fig. 3 shows that air temperature decreases slightly (1.5^{0}C) with height due to lapse rate between the canyon surface (.2m) and roof (20 m). However, the correlation between air-temperature and SVF is clear from all figures above that air temperature decreases in deeper canyons with lower SVF. Both areas represent higher air-temperature than the ambient temperature.

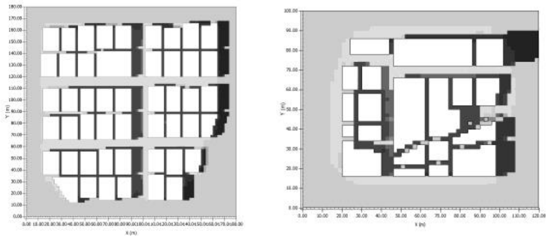

Figure 4: Comparison of MRT in Sukrabad and Baridharain N-S and E-W oriented streets

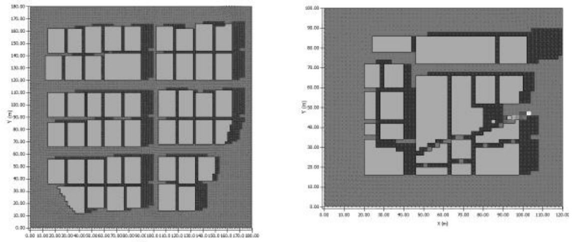

Figure 5: Comparison of Short-wave radiation at 14pm in Sukrabad and Baridharain N-S and E-W oriented streets

Comparing Fig.4 and Fig.5, it is clear that MRT is largely controlled by the amount of direct short-wave radiation and the presence of shade [6]. In Fig.4 , the MRT of sunlit areas in N-S street at 14:00pm (the hottest time of the day) in Baridhara is 35^{0}C higher than shaded parts.Findings from [7] also indicate similar differences in Colombo.The figure also indicates, N-S streets in Baridhara has lower MRT than E-W streets.The impact of orientation is also visible in Sukrabad area. In both sites, the spaces in between buildings which are constantly under shade are much cooler in comparison to the streets where H/W ratio is lower and SVF is higher. It indicates the importance of shade to lower MRT which ultimately results in better outdoor thermal comfort during daytime. MRT, 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 [11,12].

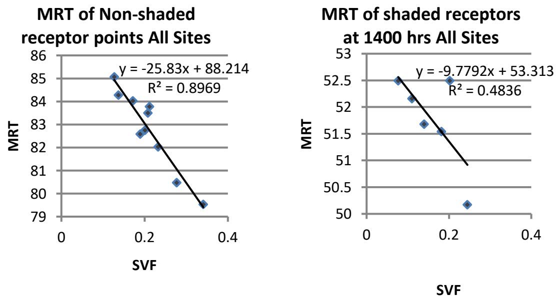

Figure 6: Comparison of SVF and MRT at 14pm in Sukrabad, and Baridharain in N-S and E-W oriented streets

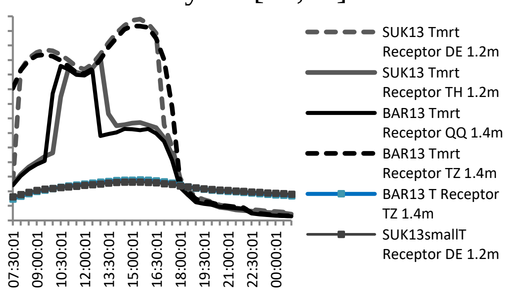

Figure 7: Comparison of MRT in Sukrabad and Baridhara

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^{0}C 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. Fig.8 suggests that ground surface temperature is almost 2^{0}C higher in the deeper canyon in Sukrabad in comparison to Baridhara. The increased surface temperature is mainly causing higher Tmrt (2^{0}C difference) in the deeper canyons. From Fig. 9 (a), (b) and (c) it is clear that in deeper canyon the amount of reflected short-wave radiation (Qsw.refl), long-wave emission of surface (Qlw.surf) and absorbed long-wave radiation from environment reaching the ground (Qlw.downTotal) is higher. This suggests a day-time urban heat-island effect in deeper canyons.

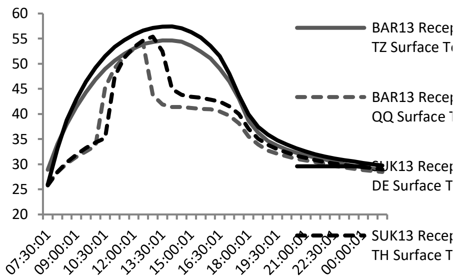

Figure 8: Surface temperature in Sukrabad and Baridhara

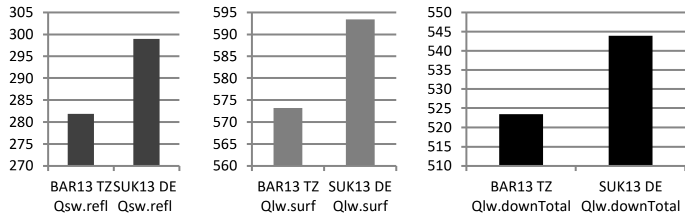

Figure 9: Comparison of Qsw.refl ,Qlw.surf and Qlw.downTotal between deeper (SUK13 DE) and shallower (Bar13 TZ) canyon

CONCLUSION

The important findings from above discussion can be summarised as follows:

- In a deeper canyon air-temperature decreased during daytime due to restricted SVF, (less than 2^0C).
- According to the simulation results, all urban canyons showed higher temperature values in comparison to ambient air-temperature over an 18 hour cycle, which suggests the impact of higher thermal storage and consequently elevated long-wave emission from the building mass in urban areas.
- The presence of direct solar radiation is the main guiding factor behind Tmrt and therefore thermal comfort. The study suggests a difference of 35^0C in Tmrt values between shaded and sun-lit areas. During the hottest time of the day at 15:00 hours, Tmrt is at least 50^0C higher for sun-lit areas and 20^0C higher for shaded areas in comparison to the air-temperature.
- Tmrt is also largely affected by orientation as orientation governs the presence of shade inside urban canyons. North-south canyons in the study areas were found more comfortable in comparison to east-west canyons.
- This result shows higher Tmrt in deeper canyons comparing different measurement points in different canyons with varying SVF values in the presence of shade. Matching correlation has been found from comparing all receptor points in the sun-lit area. This has resulted from the increase of net radiation inside deeper canyons as suggested in previous research [11,12].

It is important to note that impact of shade and the influence of H/W ration have to be dealt with separately to understand the resulting Tmrt. Several studies [2,6] have attempted to associate the reduction of Tmrt with reducing SVF or increasing H/W ratio, while this study suggests that the relation should refer to the presence/absence of shade. Increased H/W ratio can increase the mutual shading inside urban canyons and greater shade can reduce Tmrt when compared with Tmrt 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, it has to be considered simultaneously that greater depth results in higher reflection of diffused short-wave radiation and trapping of long-wave radiation from the building mass, specially in a high density context. The present arrangement in Dhaka is already very high-density, specially in terms of high land-coverage in the informal areas. Even, in planned formal residential areas like Baridhara, the FAR value is approximately 3.1 and percentage of land coverage is 61%. In this area the FAR and percentage of land coverage 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, any future steps should 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 [15] 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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