USE OF MICROCLIMATE MODELS FOR EVALUATING THERMAL COMFORT: IDENTIFYING THE GAPS

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ABSTRACT

The study identifies the gap between actual thermal sensation and theoretical comfort calculated through simulated microclimate data in different urban configurations in a tropical, high-density, megacity: Dhaka. The methodology stated here could be applied for evaluating outdoor comfort conditions for future urban areas at an early design stage. To apply the concept of theoretical comfort it is important to understand its limitations and degree of deviation from the actual comfort conditions at real scenarios. This study mainly focuses on traditional and formal (contemporary) residential settlements with different urban-geometry features. On-site climatic measurements were carried out during the hot-humid months and were compared with simulation results calculated through ENVI-met 4. Simulation results were found to have good agreement with actual air-temperature, mean radiant temperature (Tmrt) and relative humidity. In terms of windspeed, the simulated model for a complex traditional settlement did not successfully match with the actual scenarios. However, this does not affect the model competency, because, the area has rather unusual wind pattern due to its location and current arrangements of buildings. The simulated results were subsequently used to calculate outdoor thermal comfort using the PET index in RAYMAN Pro. The calculated theoretical comfort was assessed against Actual Thermal Sensation Votes (ASV) obtained through a thermal comfort survey in the case-study areas. Strong correlation (r=.58) was found between theoretical and actual comfort in the formal settlements, while the comparison with the traditional settlements produced rather weak results (r=.238). This leads to the understanding that theoretical comfort can be a useful tool for comparing between regularly planned sites; however, for complex urban geometry, theoretical comfort can deviate from actual comfort levels recorded, in part due to adaptive behaviour.

Keywords: urban geometry, outdoor thermal comfort, actual sensation vote, PET, ENVI-met

INTRODUCTION

Unbridled urbanisation, unplanned growth of built environment, acute energy shortage and elevated air-pollution levels are common problems in the high-density tropical cities located mostly in the developing countries. Such factors have adverse consequences on cities micro-climate, consequently affecting comfort levels in urban outdoor spaces as well as energy performance in urban buildings. Considering the socio-economic context of these cities, the most effective answer to the deteriorating urban micro-climate can be achieved mostly through proper urban planning and urban design. Especially, modification of urban geometry, as an urban planning tool, can play a crucial role in ameliorating the urban micro-climate. Urban micro-climate is largely determined by different components of urban geometry that includes: configuration of the streets, building heights, density and separation, roughness length and urban permeability. The effect of these components will vary according to the local climate and morphological context of the concerned area. The existing knowledge mostly concentrates on the Western (usually colder) countries and thus the strategies applied to improve their urban micro-climate are not suitable for use in tropical cities. Studies concerning tropical cities are still very limited. Therefore, insights from these cities could be valuable towards making them more liveable and resilient, so that they are able to act appropriately in response to potential challenges.

The study summarises finding from a thermal comfort field-survey and compares this with a numerical analysis. Numerical modelling and computer simulation techniques are playing increasingly important roles in current studies for predicting urban microclimate. Urban microclimate is a complex consequence of different parameters which involves innumerable natural and urban processes. Due to the complexity of diverse processes involved behind different microclimates, numerical methods are becoming more acceptable now-a-days. However, the application of physical data from the models for predicting pedestrian thermal comfort conditions is a rather new area of research and could be a useful tool for comparing between different sites which have variable urban morphology. Therefore, in this study theoretical comfort model has been compared against actual thermal comfort level. Previous studies in this field have compared theoretical comfort index (PMV, PET) with actual comfort, but using on-site microclimate data instead of simulated data [1,2]. The methodology followed in this study could be applicable for understanding outdoor comfort conditions for virtual environments for still unbuilt areas at the design phase.

SITE SELECTION AND METHOD

The study focuses on the tropical megacity Dhaka. The city falls under tropical Monsoon climate with a distinct warm-humid rainy season, a hot-dry summer and a short cool-dry or winter season. The mean annual temperature is 25.8^{0}C with an annual range between 8.2^{0}C to 39.4^{0}C. The mean annual relative humidity is 75%.

Figure 1. Typical formal areas: a)FRA_1_EW, b) FRA_2_EW, c) FRA_2_NS

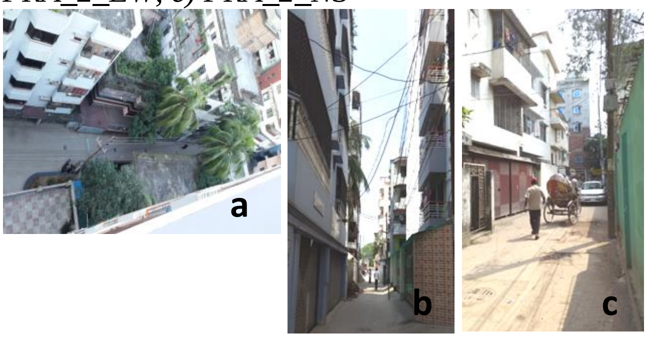

Figure 2. Typical traditional areas: a)TRA_1_EW, b) TRA_1_NS, c) TRA_2_NS

Two sets of residential settlements: traditional and formal, were selected for the study. Table 1 lists the site names, abbreviations and their common geometric characters. In general, formal residential areas, which evolved from urban planning regulations, are characterised with buildings of equal height and width, with roads laid out in a grid-iron pattern (Fig 1). Traditional residential areas on the other hand, mostly resulted from spontaneous developments under loose planning controls; have variable building forms, heights, plot sizes and even different building usage (Fig 2). While both settlements have compact design, high H/W ratio (building height/ street width) and lack of vegetation, the former (formal) is mostly uniform and the latter is quite diverse and variable.

Measurements were carried out in north-south (NS) and east-west (EW) oriented streets in two traditional and two formal sites during the hot-humid month in September. These included air-temperature (T_a), humidity (RH), globe temperature (T_g), mean radiant temperature ($Tmrt$) and windspeed

(V). Instruments used in the study were: tiny-tag air-temperature and humidity data loggers and OM-CP-WIND101A data logger with a 3-cup anemometer. Globe temperature was measured using Tiny-tag data-loggers with a thermo-couple thermistor probe inserted inside a 40mm (D= dia= 0.04m) globe painted in Humbrol matte grey (ε = emissivity =0.97). Subsequently, Tmrt was measured using the following formula:

$$\text{Tmrt} = \left[\frac{\left(T_g + 273\right)^4 + (1.10 \times 10^8\, V^{0.6})(T_g - T_a)}{(\varepsilon\, D^{0.4})}\right]^{1/4} - 273$$

A questionnaire survey was carried out along with physical measurements among 339 people. Pedestrians were asked about their thermal sensation. The actual thermal sensation vote was analysed according to ASHRAE seven point thermal sensation scales [3].

Typical values from site measurements were used to set up the boundary conditions for the micro-climate simulation tool ENVI-met 4. ENVI-met is a numerical microclimatic tool with high temporal and spatial resolution that is able to recreate the major microclimatic processes inside complex urban arrangements [4]. In order to examine comfort conditions in outdoor spaces, this study adopted PET (Physiologically Equivalent Temperature) [5]; a widely used thermal comfort index based on the Munich Energy-balance Model for Individuals (MEMI). The simulated climatic data calculated by Envi-met that included Ta, RH, Tmrt and V was used as an input for PET calculations in Rayman Pro [6].

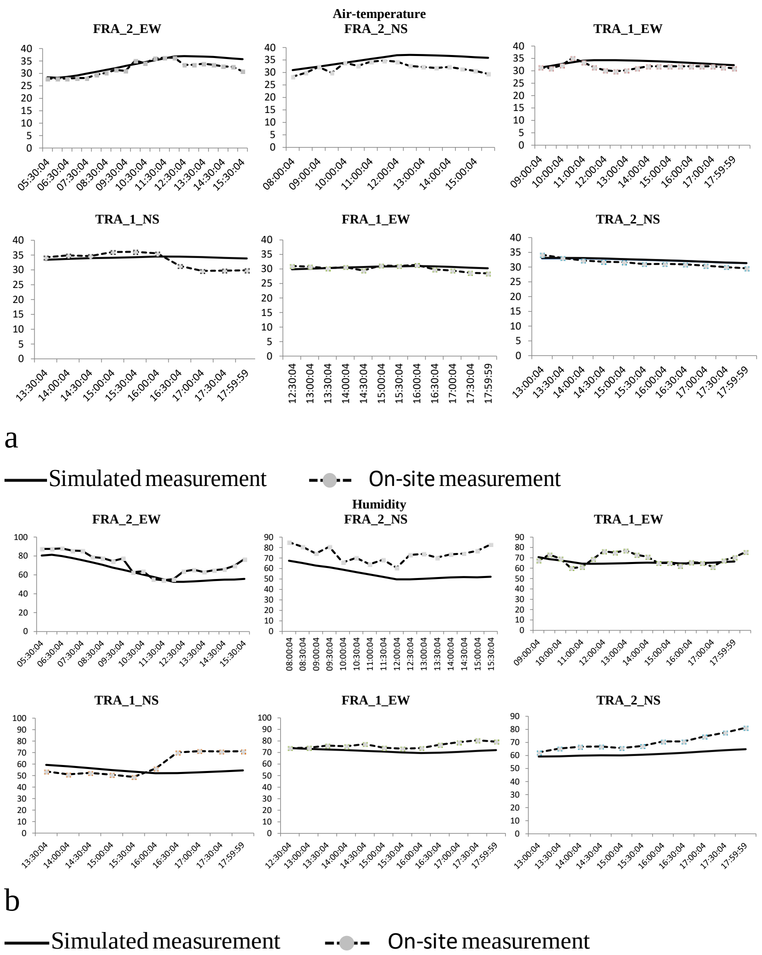

Figure 3: Simulated versus on-site measurements of a) air-temperature, b) humidity

RESULTS

Micro-climatic simulations using ENVI-met for the hot-humid climate of Dhaka is validated through the current study by comparing actual on-site measurements with the simulated measurements of the climatic variables. Comparison of air-temperature, humidity and Tmrt led to the conclusion that simulation results were in good agreement with actual measurements (Fig. 3, Fig 4). Only exception was FRA_2_NS where humidity and Tmrt was over estimated by simulation. This can explained by the fact that simulation models were kept as simple as possible due to their long running time. Therefore, due to their simplicity, the exact character, number and position of plants are not identical to the actual sites. Plant sizes and their positions seem to have affected the humidity and Tmrt levels.

Another anomaly was identified regarding windspeed in traditional areas that are more diverse in character (TRA_1_EW, TRA_1_NS). Simulated results, in this case, deviated quite extensively from the actual values. It is one of the model limitations that the windspeed and direction at the model boundary remains constant throughout the simulation period although this is modified inside the model depending on the presence of 3 dimensional objects. This indicates the calculation of windspeed using ENVI-met can be somewhat compromised for very complex urban geometry. It is also important to remember that simulations tools are mainly for understanding the trend of microclimate, rather than generating actual numbers. However, the model is not solely accountable for the deviation. Most other micro-climatic sites in the city were found to have very low windspeed, while, the site in question was reported with high turbulence during the survey. Therefore, none of the other sites were affected by the fact. The reason why windspeed was higher in the particular site is due to the fact that the site is located next to an abandoned airport, making the north-west side of the area totally open. This makes the wind-pattern in the area rather unpredictable. Accurate windspeed prediction of the area will mean modelling of entire the urban district in a very high resolution. The necessary modelling time and computer power is beyond the scope of this research.

PET was compared with ASV for all case-study areas and a moderate (spearman's rho = 0.348) but significant correlation (p-value = 4.883e-11) was found. This finding suggest theoretical comfort calculation will follow the similar trend as the actual comfort sensation of the pedestrians, but the latter may not be fully explained by physical conditions only. Afterwards, PET was calculated separately for the traditional and formal areas. For formal areas a stronger (spearman's rho = 0.58) and significant (p-value < 2.2e-16) correlation was seen between PET and ASV. This is due to good agreement between micro-climate variables in simulated models and actual measurements. Also, the comparatively simpler geometry in the formal areas aided analysis and understanding of the outdoor comfort conditions through theoretical calculations.

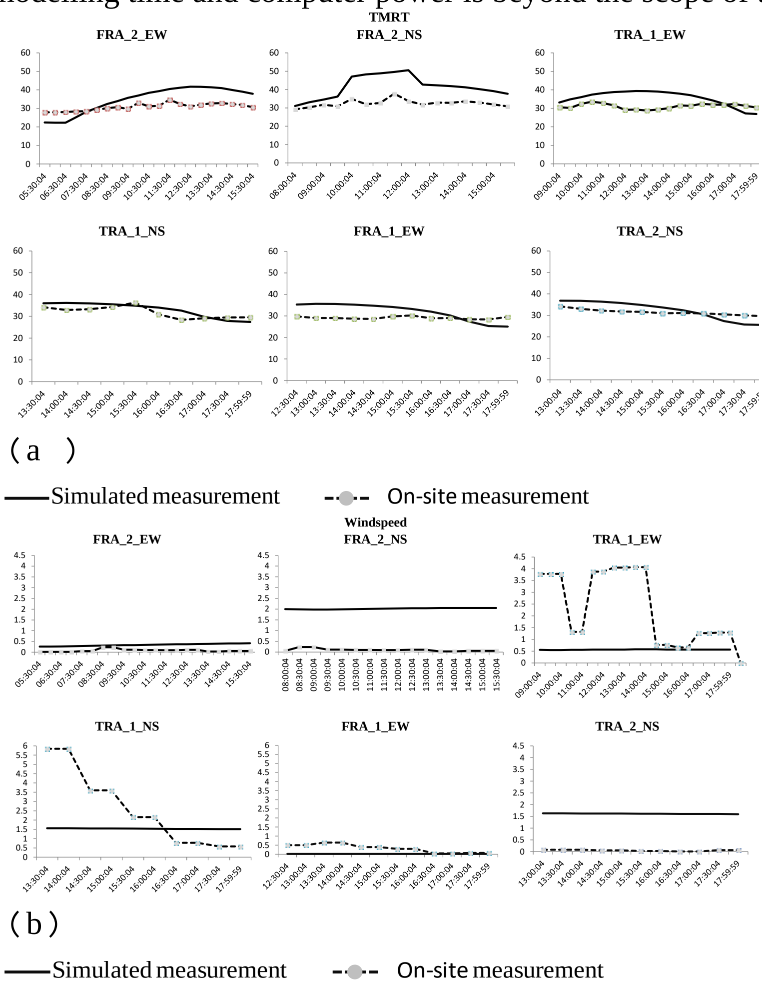

Figure 4: Simulated versus on-site measurements of a) Tmrt, b) windspeed

Within traditional areas, especially in TRA_1_EW, TRA_1_NS, simulation model was still able to predict the micro-climatic variables quite competently except for the windspeed, as discussed previously. Windspeed is an important parameter for outdoor thermal comfort and was somewhat compromised in the micro-climatic simulations. Since, simulated windspeed was lower in case of TRA_1_EW and TRA_1_NS and higher in TRA_2_NS than the actual values (Fig. 4) PET was slightly overestimated in the first two cases and under-estimated in the third case respectively.

	MICRO-CLIMATE SITE NAME	ABBREVIATED NAME	H/W RATIO	SVF
1	TRADITIONAL RESIDENTAL AREA 1 EAST-WEST_ SOUTH1 KAFRUL	TRA_1_EW	2.6	0.177
	TRADITIONAL RESIDENTAL AREA 1 NORTH-SOUTH_ SOUTH KAFRUL	TRA_1_NS	2.5	0.231
2	TRADITIONAL RESIDENTAL AREA 2 NORTH-SOUTH _ MID KAFRUL	TRA_2_NS	3.5	0.149
3	FORMAL RESIDENTIAL AREA 1 EAST-WEST_MAHAKHALI DOHS	FRA_1_EW	2.4	0.201
4	FORMAL RESIDENTIAL AREA 2 EAST-WEST_BARIDHARA DOHS	FRA_2_EW	1.8	0.229
	FORMAL RESIDENTIAL AREA 2 NORTH-SOUTH _BARIDHARA DOHS	FRA_2_NS	1.2	0.259

Table 1. Site names, abbreviations and urban geometry characters

Subsequently, statistical analysis in the traditional sites between PET and ASV produced weak (spearman's rho =.238) but significant (p value = 0.003) correlations. Apart from the physical microclimate, ASV seems to be deviated from PET for the effect from thermal adaptation as well. The roads in these areas being quite narrow and deep were able to cut down large amount of solar radiation. However, other factors like higher traffic and absence of pavements may have affected the ASV in TRA_2_NS, while the other two streets (TRA_1_EW, TRA_1_NS) were not affected due to lower traffic.

Thermal sensation	PET range
Cold	14-18
Cool	18-22
Slightly cool	22-26
Neutral	26-30
Slightly warm	30-34
Warm	34-38
Hot	38-42
Very hot	<42

Table 2. PET range for Taiwan

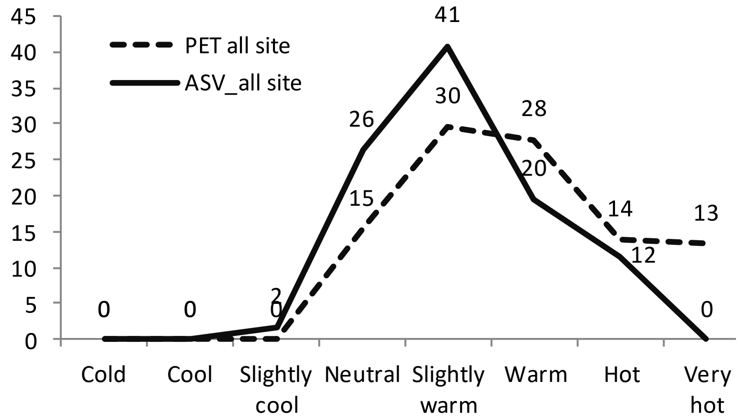

Figure 5: Comparison of ASV and PET (percentage) all sites

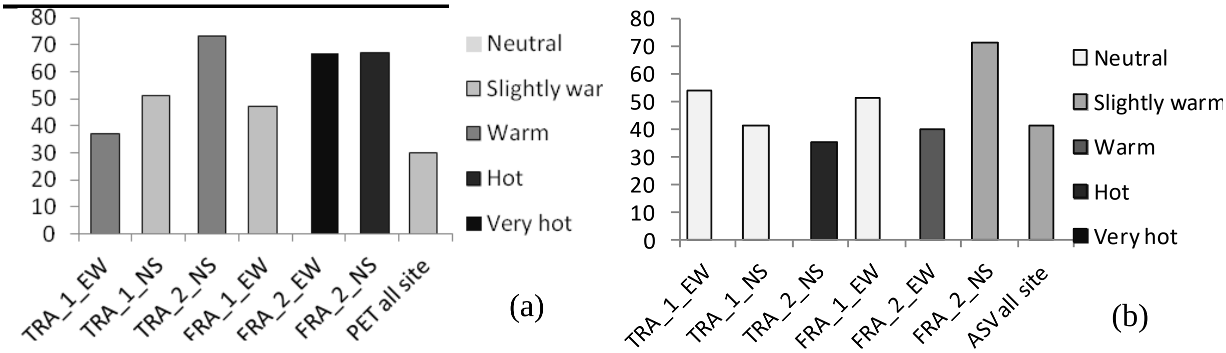

Figure 6: Compare peak thermal sensation in each site for PET(a) and ASV(b) analysis

For the hot-humid climate of Dhaka, comfortable temperatures for outdoor conditions ranges from 28.5^{0}C to 32^{0}C at an average relative humidity of 70% under still air conditions for people wearing typical summer clothes (0.4 to 0.5 Clo) and involved in sedentary activities [7]. This comfort range is not categorised for PET index. In the absence of a 'PET range' for Dhaka, the scale developed for Taiwan (warm-humid sub-tropical region) has been used in this study [8]. The PET data was arranged according to the PET range and ASHRAE seven point thermal comfort scale and then compared with the ASV data collected through the questionnaire survey. The comparison of shows that in both analyses most people were found to be feeling 'slightly warm': 41% for ASV and 30% for PET analysis (Fig 5). However, the PET analysis slightly overestimates people feeling ‘warm’ and ‘hot’ and highly overestimates people feeling ‘very hot’. In the actual survey, none of the subjects reported feeling ‘very hot’.

The peak thermal sensation for both ASV and PET analysis on site by basis are also compared to each other (Fig 6). Thermal sensation was over estimated for each of the sites by PET analysis, except TRA_2_NS. For example, the peak thermal sensation for TRA_1_EW, TRA_1_NS and FRA_1_EW were ‘neutral’. But this has been replaced by ‘warm’, ‘slightly warm’ and ‘slightly warm’ respectively. It is anticipated that the road conditions, pavements and traffic, as mentioned before, have further modified the thermal comfort levels apart from the micro-climate. The other formal areas FRA_2_EW and FRA_2_NS were highly overestimated by PET, especially, for the east-west streets, although the micro-climate was quite accurately predicted in the simulated model. The use of a PET range from a different city may have affected the results to some extent. This still indicates, theoretical comfort largely ignores the thermal adaptation level of the pedestrians in a tropical climate.

CONCLUSION

Numerical simulations in this study were found to be in good agreement with actual microclimate measurements. Theoretical comfort calculated using simulated data, on the other hand produced mixed results depending on the site geometry. For simple urban geometry in the formal areas, the results were strongly aligned with actual measurements, although overestimated. For complex geometry in the traditional areas, a poor correlation was reported and the results deviated significantly. This indicates, as long as microclimatic simulations are closely correlated with actual measurements, theoretical comfort (PET) will follow a similar pattern as the actual comfort (ASV). However, this does not mean PET values will be identical to the ASV values. In fact, for most of the microclimates sites PET was overestimated in relation to ASV. Previous studies have also demonstrated that a solely physiological approach is insufficient to understand comfort conditions outdoors [1]. This suggests that theoretical comfort models can be applicable for obtaining a relative understanding of comfort situations at urban outdoors; however, they can vary considerably from actual thermal sensations due to the role of thermal adaptation.

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