Harmonious accordance of indoor-outdoor thermal comfort and building energy performance by ameliorating urban microclimate in different urban block types in tropical climate

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ABSTRACT

This paper explores the effect of outdoor microclimatic environment upon indoor conditions for different urban block types in hot-humid climate. The main focus here is on courtyard patterns, considering its potentials for hot-humid climate is not fully understood yet. Courtyard spaces have been examined in conjunction with the internal spaces of surrounding buildings with the aim to create a link between both. Based on theoretical models, it intends to devise strategies to optimise both indoor-outdoor thermal comfort and building energy performance while enabling the building designers and urban professionals to consider these essential issues at the early design stage. For this study, four simplified archetypal urban arrays are selected, primarily developed by Martin and March. These are: pavilions, enclosed courtyard pavilions, open-square and open-rectangular courtyard pavilions. Firstly, it has observed the microclimatic characteristics of the geometric patterns through a high resolution CFD microclimatic model: ENVI-met. Thermal comfort in the adjacent and enclosed outdoor spaces was assessed against Physiological Equivalent Temperature (PET) index with the aid of Rayman 1.2. Secondly, the energy performance of the surrounding buildings was analysed by IES-VE: a building performance modelling tool. The methodology and results from the current study can be integrated in the future urban planning processes in a high-density warm-humid context.

Introduction

Courtyards are common urban arrangements; often regarded as micro-climate modifiers. The application of courtyard houses for hot-arid climate, in particular, is well-established and well-documented. But there is disagreement (Ratti, Raydan, and Steemers 2003) for the same in hot-humid climate due to little diurnal variation which may result in urban heat island effect and reduced wind effect. Meir, Pearlmutter and Etzion (1995) has also emphasised, courtyards can only act as micro-climate restoratives, when certain conditions are met .This opens up a prospect to look at courtyard arrangements again by altering its basic parameters such as, geometry, permeability and orientation. Since this pattern has been practiced in the stated climate for many years, specially in the vernacular architecture (Figure 1 b, c), it could be interesting to investigate how far they are applicable in terms of outdoor and indoor thermal comfort and building energy performance in an urban context. It is very unlikely that the same courtyard suitable for hot-arid climate will also be the best option for hot-humid climate.

Outdoor thermal comfort is particularly significant in hot-humid climate as outdoor spaces can be used all throughout the year, except the presence of rain. It has a clear repercussion on people’s behaviour and usage of outdoor spaces and can help to support social, economic and cultural vitality. But very limited number of study has intended to incorporate the outdoors with indoors. It is indeed difficult to attain an ideal harmony

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between them in a complex urban environment.

The main inconsistency arrives at urban block level, between urban design and architecture with conflicting interests which may often eliminate each other. The former often tries to promote the outdoor environment, whereas the latter focuses on indoors. The physical configuration of urban patterns to reduce building energy demand and augment indoor comfort is not always compatible with comfort requirements in outdoor spaces. For example, in tropical climates, creating mutually shaded urban spaces to ensure comfortable outdoors can lead to north-south orientation of buildings. This means higher solar exposure on building facades which results in elevated building temperature and larger energy consumption. There is still need for a holistic approach where a synergy is created among these heterogeneous parameters, specially at the urban block level, so that the effect of a single block's performance can be achieved over the entire city.

Another limitation in the current research is, most studies on energy performance of buildings concentrate on individual buildings while its interaction with neighbouring urban context remains largely unexplored (Ratti, Baker and Steemers 2005, Futcher, Kershaw and Mills 2013). Buildings are considered as isolated masses, disregarding the fact that they belong to an urban environment. Consequently, the energy performance of buildings is generally analysed with the aid of general climatic data, in case of building simulations in particular, which varies significantly with micro-scale climates. Indoor conditions are determined through the interaction between the building surface and meso-climatic data uploaded as a weather file. Predicted energy consumption this way by ignoring its urban settings can vary significantly from the actual value (Norford *et al* 1994, NBI 2008, Moonen 2006). As suggested by Givoni (Cited in Ratti, Baker and Steemers 2005): “The outdoor temperature, wind speed and solar radiation to which an individual building is exposed is not the regional ‘synoptic’ climate, but the local microclimate as modified by the structure of the city, mainly of the neighbourhood where the building is located”. Therefore, in this study, the microclimatic data calculated from ENVI-met was used as input for calculating energy load for the buildings at strategic positions inside the urban blocks.

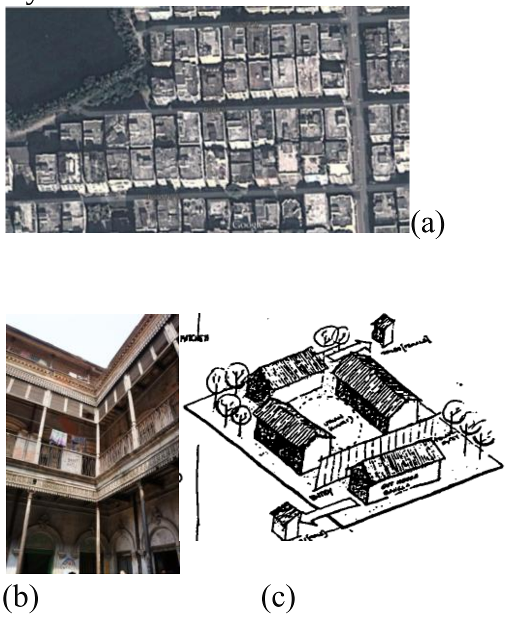
Methodology

Unlike previous studies, the interest of this study extends beyond evaluating courtyard spaces individually to an array of multiple courtyard pavilions in urban levels. Since this can only be achieved hypothetically, numerical modelling and computer simulation techniques were adopted in this study. Numerical modelling is more convenient in terms of comparing theoretical models with different combination of parameters. The real situation is always so complex that often the main parameter remains obscured. The results from simulations, on the other hand aids to attain a clearer understanding of the effect of most relevant parameters. Due to the complexity of diverse processes involved behind different microclimates, it is no longer feasible to assess their impacts without the help of numerical methods (Bruse 1999). Therefore, ENVI-met, a numerical microclimatic tool with high temporal and spatial resolution was applied in this study as the main tool to measure microclimatic dynamics.

In order to examine comfort conditions in outdoor spaces, this study adopted PET (Physiologically Equivalent Temperature) (Höppe 1993), which is a widely used thermal comfort index based on the Munich Energy-balance Model for Individuals (MEMI). The simulated climatic data calculated by Envi-met was used as an input for PET calculations in Rayman (Matzarakis and Rutz 2006), which included air temperature, wind speed and direction, relative humidity and mean radiant temperature.

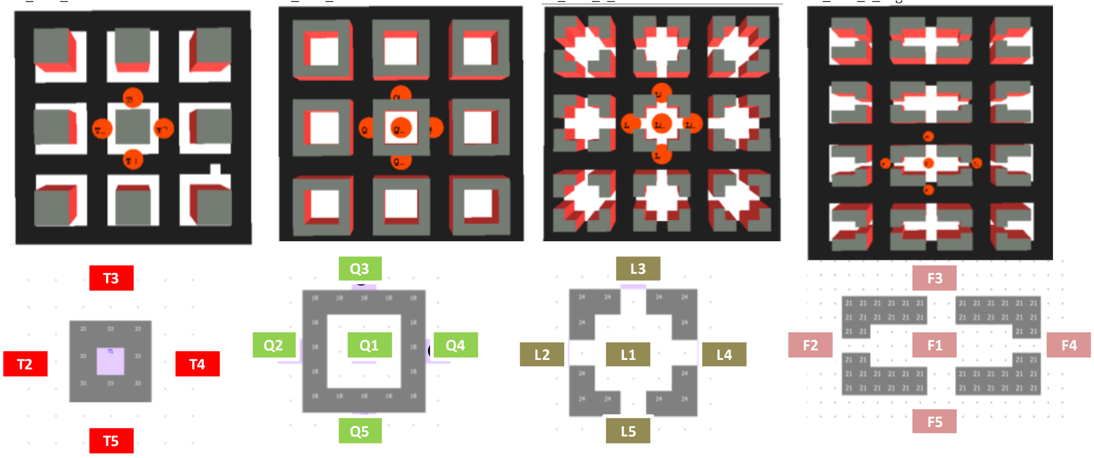
Finally, the energy performance of the buildings is evaluated with IES-VE (Integrated Environmental Solutions-Virtual Environment), a dynamic thermal simulation tool, extensively used in contemporary research and practice. The application of IES was confirmed for tropical hot-humid contexts (Al-Tamini and Fadzil 2011). Its ability in reproducing the performance of multiple buildings within an urban context while considering the mutual shading and radiation exchanges between buildings (Futcher, Kershaw and Mills 2013) made it particularly appropriate for the current study.

Four archetypal urban arrangements, from Martin and March (1972) have been investigated in this study under the hot-humid climate of Dhaka. This includes: pavilions, enclosed courtyard pavilions, open square and open rectangular courtyard pavilions. Although the first type does not belong to a courtyard category, it has been included as this is the most common urban type in the case study area, Dhaka (Figure 1 (a)). It is therefore important to compare its performance with courtyard types. The second type is mostly suitable for hot-arid climate and also visible in many modern and historic building arrangements in hot-humid climates (Figure 1 (b)). The third urban type is an altered and urbanised pattern of rural housing arrangements in the case study area (Figure 1 (c)). In the latter, openings are provided in the corners of the courtyard, whereas in the former, opening is placed across the centre. The fourth type has been generated by elongating the third type along east-west direction since, building forms stretched out along the east-west direction are considered to be better suited for the majority of climates (Olgyay 1963).


(a)

(b) (c)

Figure 1 (a). Most typical urban arrangement in the case study area, representative of pavilion pattern, (b)Historical building with enclosed courtyard in case study area (c)Typical vernacular residential arrangement with openings at four corners of the courtyard,



Model 1 **Model 2** **Model 3** **Model 4**

Figure 2. Four archetypal urban arrangements in Envi-met with their measurement points (receptors)

Outdoor simulation by Envi-met. In this paper, outdoor microclimate (at a height of 1.5 m) has been calculated with the aid of ENVI-met Version 4. ENVI-met, Version 4 is able to consider the heat capacity of the walls in the calculations. Climatic variables such as, air temperature, relative humidity, wind speed and direction, specific humidity data were collected from standard .epw weather file for Dhaka for the test day, assuming the worst-case scenario. Solar radiation was calculated in Envi-met using the location data and simulation date of the case-study area. Simulation was carried out during a hot-summer day, with the highest maximum air-temperature in early-April when a high air temperature is coupled with high relative humidity and creates a challenging comfort environment .The input data for Envi-met simulation are shown in Table 1.

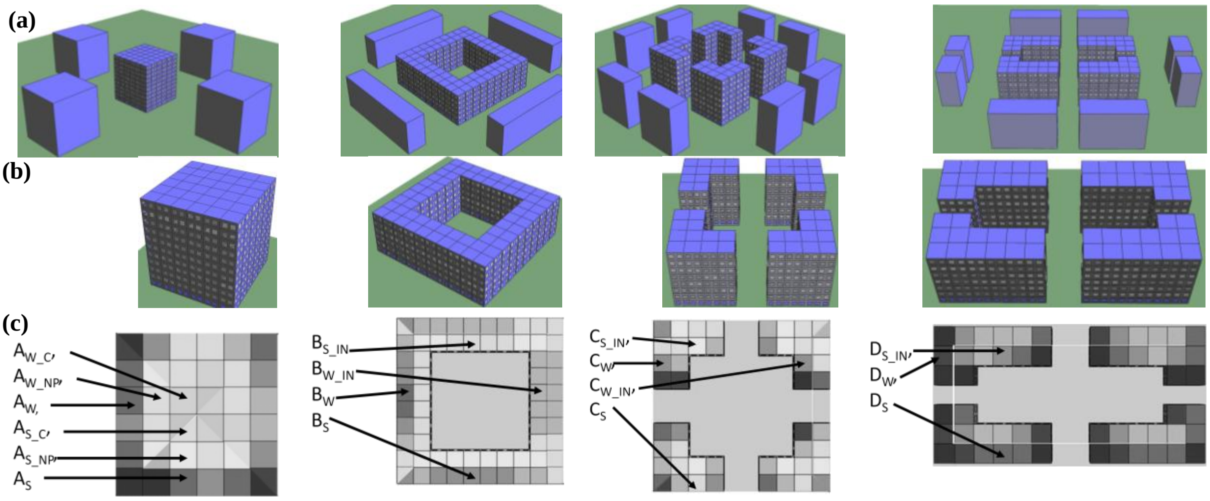
Nine groups of buildings are arranged in each urban type, except the fourth-type because of its elongated shape. Only the middle cluster is taken into account in each case. This is to include mutual shading and wind effects from its surroundings and to avoid perimeter effects. All building clusters have same Floor Area Ratio (FAR, ratio of total floor space to site area). Building height and site coverage were adjusted accordingly.

Table 1: Input data for Envi-met Simulations

1. Building Material	Wall-Brick Wall(burned), Roof-Concrete Wall (Cast dense)	**14. Simple Forcing: Highest Humidity**	87% at 6:00am
2. Soil	Road-Asphalt, Pavement-Paved Concrete-Grey	**15. Simple Forcing: Lowest Humidity**	43% at 3:00am
3. Start Date, Start Time, Total Simulation Hour	05-04-2013, 06:00:00, 24	**16. Solar Radiation**	Default
4. Wind Speed measured in 10m height (m/s)	3	**17. Clouds**	Default
5. Wind |Direction (deg)	145	**18. Turbulence Model**	Default
6. Roughness length at measurement site	0.01	**19. Lateral Boundary Conditions**	Default
7. Initial Temperature of Atmosphere (K), **8. Calculated when forcing is used**	32 Deg C	**20. Model Timing: Dynamic Time-step Management**	T0=2, t1=1, t2=1
9. Specific Humidity at model top (2500m, g/kg)	8	**21. Update timing**	Default
10. Relative Humidity in 2m (%), **11. Ignored when forcing is used**	67.96	**22. Soil and Plants: Initial conditions for soil**	Default
12. Simple Forcing: Highest Temperature	310.90 K (37.9 Deg C) at 3:00pm	**23. Settings plant model**	Default
13. Simple Forcing: Lowest Temperature	299.40K(26.4 Deg C) at 6:00am	**24. Pollutant dispersion**	Default

Table 1: Input data for Envi-met simulation

Indoor simulation. In order to examine the impact of outdoor micro-climate conditions inside building interiors, the urban arrangements were recreated in IESVE. All building material and opening types and percentage of opening area were kept similar in all models for easy comparison. Keeping the target building at the centre, solid blocks were put in the surroundings to calculate shading impact of adjacent buildings using Suncast link. Wind exposure was changed from semi-exposed to sheltered to account for the adjacent building and the blocking amount.



(d) FAR= 3.84	FAR= 3.84	FAR= 3.84	FAR= 3.84
Site Coverage 36%	Site Coverage 64%	Site Coverage 48%	Site Coverage 57%
Height 11 Floors	Height 6 Floors	Height 8 Floors	Height 7 Floors
Model 1	**Model 2**	**Model 3**	**Model 4**

Figure 3. (a)showing urban blocks, (b)detail blocks, (c)location of examined rooms, (d)building density

Use of climatic data. Instead of the standard .EPW climatic file for the case study area, micro-climate data calculated by Envi-met was used for building simulations in IES.

Therefore, it was not necessary to create the whole urban pattern in IES-VE as in Envi-met model, since the urban effect is already included by the use of this micro-climate data. For example in Model 2, room conditions (those facing the courtyard) were analysed using microclimate data from receptor Q1, located at the centre of the courtyard at Model 2 in Envi-met (Figure 2). For investigating rooms adjacent to the north-south and east-west oriented streets, data from receptor Q4 and Q5 were used respectively. Same process was followed in all models. In total, 22 building simulations were done for over 1556 zones using microclimate data from the respective Envi-met model.

Table 2: showing investigated room name list and their abbreviated format, associated models and receptors

Model Name	**Room Name**	**Abbreviated Room Name**	**Receptor**
Model 1	Model 1 West-facing Non-passive	A_{W_NP}	T4
Model 1	Model 1 West-facing Core	A_{W_C}	T4
Model 1	Model 1 West-facing	A_W	T4
Model 1	Model 1 South-facing Non-passive	A_{S_NP}	T5
Model 1	Model 1 South-facing Core	A_{S_C}	T5
Model 1	Model 1 South-facing	A_S	T5
Model 2	Model 2 South-facing Inside Court	B_{S_IN}	Q1
Model 2	Model 2 South - facing	B_S	Q5
Model 2	Model 2 West-facing	B_W	Q4
Model 2	Model 2 West-facing Inside Court	B_{W_IN}	Q1
Model 3	Model 3 South-facing Inside Court	C_{S_IN}	L1
Model 3	Model 3 South - facing	C_S	L5
Model 3	Model 3 West-facing	C_W	L4
Model 3	Model 3 West-facing Inside Court	C_{W_IN}	L1
Model 4	Model 4 South-facing Inside Court	D_{S_IN}	F1
Model 4	Model 4 South - facing	D_S	F5
Model 4	Model 4 West-facing	D_W	F4

Table 3: Model Set-up for IESVE model

Building Template Manager: Thermal Conditions
▪ **Building regulations:** Heated or occupied room ▪ **Room conditions:** ○ **Heating**: Heating Profile> Off continuously ○ **DHW**: Consumption> Independent Profile ○ **Cooling**: cooling profile> Cooling System Profile_Dhaka Weekly ○ **Simulation cooling setpoint (^{0}C):** 28^{0}C ○ **Plant** (auxiliary energy)> Off continuously
System
▪ **HVAC system**> Dhaka cooling ▪ **Auxiliary vent**> Dhaka cooling ▪ **DHW system**> None ▪ **Cooling system**: ○ Cooling mechanism: air-conditioning ○ Fuel: electricity ○ Aux energy: Fans> Centralised balanced A/C or mech vent system Air-supply: external air
Air Exchanges
▪ **Infiltration** Max Fow: .167, Unit: ach, on continuously, Adjacent condition: external air
Internal gain
▪ **Fluorescent Lighting:** Reference : .7- Multifamily Lighting, Max sensible-7.535 W/m2,Max power-7.535 W/m2, Rad Frac-.45,Fuel- Electricity, Variation- Domestic Ligthing Profile, Dimming- on continuously ▪ **People:** Reference: 220-Multifamily Occ-166, Max sensible-64.476 W/person, Max Latent Gain-29.307 W/person , Occupancy- 15.422 m2/person ,Variation- Domestic Occupancy Profile, ▪ **Miscellaneous:** .5-Multifamily Equip, Max sensible-5.382 W/m2, Max Latent Gain –0 W/m2, Max power- 5.382 W/m2, Rad Frac-.22, Fuel-Electricity, Variation- Domestic Miscellaneous Loads Profile
Construction
▪**Roof**: 8 in. Light Weight Concrete ▪**Ground /exposed floor**: Un-insulated solid ground floor ▪**Internal floor/ceiling**: 8in. Light Weight Concrete Floor Deck, U – value: 1.361 ▪**External Wall**: Brickwork Single –Leaf Construction Dense Plaster, U – value: 2.184 ▪**Glazing**: 6 mm Pilkington Single Galzing, U value-5.562 ▪**Wooden Door**: U-value: 2.194 ▪**Internal Partition:** 13mm pll 105mm bri 13mm pll, U value: 1.473 ▪**Internal glazing:** 4mm Pilkington single glazing, U value: 3.689

Climatic variables that were altered with micro-climatic data are air-temperature, humidity, wind-speed and wind-direction. Air-temperature and humidity were measured at 1.5m height, whereas wind data was measured at 10m height as a standard practice in calculating weather variables. Solar radiation was kept same as the original .epw file and was further modified by IES-VE simulations depending on surrounding geometry and mutual shading between buildings.

Figure (3-c) shows the location of each model room and Table (2) shows the information which receptor data was used to calculate which room with their model names. In order to understand the mutual-shading effect, only rooms located at the 2nd floor were considered in this study.

Indoor conditions are calculated for HVAC mode, using cooling energy or air-conditioning. Thermal conditions, system details, internal gain, air-exchange and construction details for are listed in Table 3. Cooling system is activated when indoor temperature reaches 28^0C. At other conditions, when T_a lies between 24^0C to 28^0C and T_a is greater than T_o, natural ventilation is activated through openable windows.

Model room shape and size. All models are consisted of same size rooms of 5m X 5m area, with 3m height. Rooms were divided in two categories: passive and non-passive. Those along the building perimeters, with 5m depth, are passive rooms, whereas, rooms without access to outer periphery are termed as non-passive.

Results of Outdoor Thermal Comfort Analysis

Results are analysed in terms of air-temperature, wind speed, Tmrt and PET for outdoor environment. While calculating the PET, the above parameters are taken into account besides vapour pressure and relative humidity for a 35 year male (height 1.75m, weight 75kg and .5 Clo) engaged in sedentary activity (80 Watts).

For the hot-humid climate of Dhaka, access to air-flow and protection from solar radiation are two main parameters to achieve comfort at outdoor spaces. Comfortable temperature for outdoor conditions ranges from 28.5^0C to 32^0 C at an average relative humidity of 70% under still air conditions for people wearing typical summer clothes (.4 to .5 Clo) and involved in sedentary activities (Ahmed 2003).

Air-Temperature. The temperature difference between the different sites is quite insignificant as the input data (standard .epw file for Dhaka) is assumed to be the same for all simulations at different sites of similar building density (Figure 4). Consequently, air-temperature within all receptors follows a similar pattern. This is in agreement with previous studies (Ali-Toudert and Mayer 2004) which confirm air-temperature as an weak indicator of thermal comfort for outdoor spaces as it is insignificantly changeable with urban configuration. For actual sites, the input data may vary due to different building materials, vegetation and other parameters, subsequently affecting the air-temperature to some extent. However, in simulation models, building-blocks were simplified and material was kept the same in order to understand the relative impact of urban configuration rather than understanding the effect of other parameters.

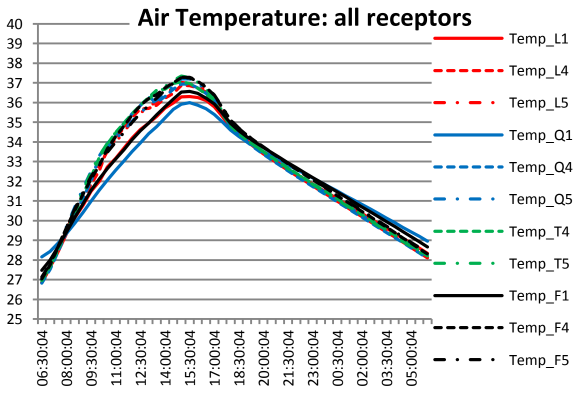


Figure 5. Air-temperature pattern in all receptors

Wind-speed. In the hot-humid climate of Dhaka, higher wind-flow is preferred for outdoor thermal comfort. As can be seen in Figure 6, the prevailing wind-flow affects different urban patterns in different ways. In Model 1, streets have higher wind speed than other models, because, its greater width and continuous facade facilitates easy wind channelling. Model 2 also offers continuous wall facade, thus providing higher wind speed in north-south streets. For higher amount of perforation, Model 3 and 4 have lesser wind-speeds inside the streets.

All model streets along east-west direction have lower wind-speed in comparison to the ones along north-south direction, because the wind is coming from the south-east direction. In terms of the courtyard spaces, Model 2 offers the worst condition at the centre of the courtyard with an average wind-speed of .15 m/s (Figure 7). Wind-shadow across Model 4 courtyard is greater than Model 3 for its smaller gaps across east-west direction.

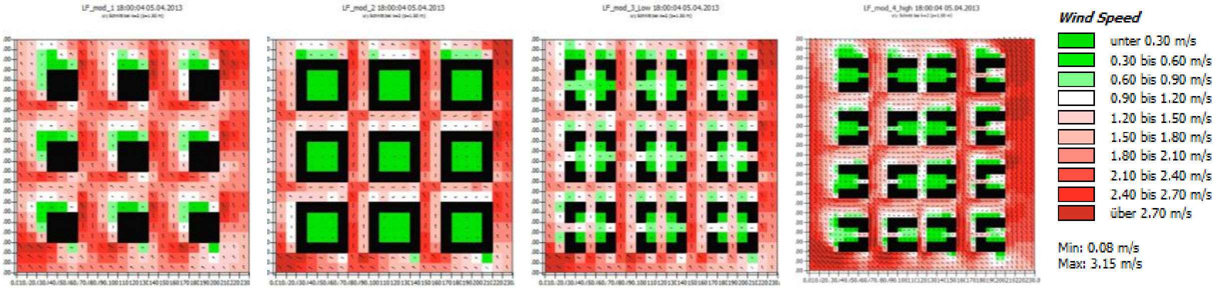


Figure 6. Wind-speed in different urban arrangements

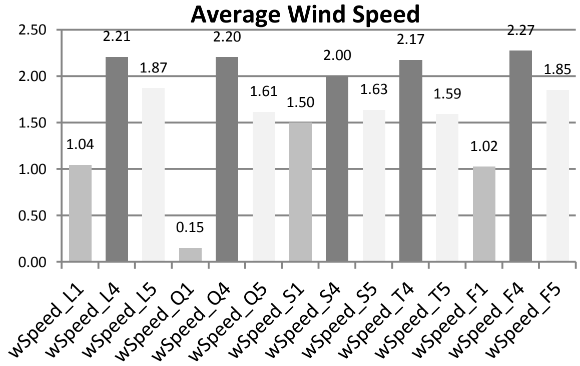


Figure 7. Average wind-speed in all receptors

Mean radiant temperature (Tmrt). Tmrt is identified as the most significant factor in determining comfort levels in outdoor thermal environments (Matzarakis and Rutz 2006) which can be twice as important as air-temperature in the case of tropical climates (Szokolay 2004). Tmrt is largely controlled by the presence of shade. In Figure 8, areas with lower Tmrt are representative of shaded areas which suggests Tmrt can vary from 35^0 to 20^0 C between the shaded and sun-lit spaces.

Apparently, the amount of shade is lowest in the rectangular courtyard in Model 4 at 1500 hours due to its elongation towards east and west, while Model 2 courtyard has the highest shade and thereby the lowest Tmrt. Among all four models, Tmrt is highest in Model 1, due to lack of mutual shading in the streets as well as the building surroundings, thus making it the worst arrangement in terms of outdoor comfort.

PET analysis. Figures 9 gives the temporal evolutions of PET index for receptors**.** It shows, PET in the middle of the enclosed courtyard (Model 2, receptor Q1) is the highest among all receptors throughout the day ranging from 63^0 to 72^0 C between 9:30 to 14:30 pm. Whereas, the same in the middle of open-square courtyard (Model 3, receptor L1) ranges between 57^0 to 64^0 C during 10:00 am to 14:00 pm. This is on average 6^0 C lower than Q1 for the main part of the day and the length is also 1 hour shorter. This difference is visible when both receptors are exposed to direct sun. This means, the difference is occurring due to lack of air-flow inside Model 2. Although, receptor L1 shows higher PET during the morning and afternoon in comparison to receptor Q1, there are other shaded spaces inside the open- square courtyard area and the users have choice to move into those areas (Figure 6).

PET mainly varies depending on the presence of shade. For example, at 1500 hours the difference of PET between receptor Q1 (under sun) and receptor T4 (under shade) is around 28^{0}C (Figure 9).

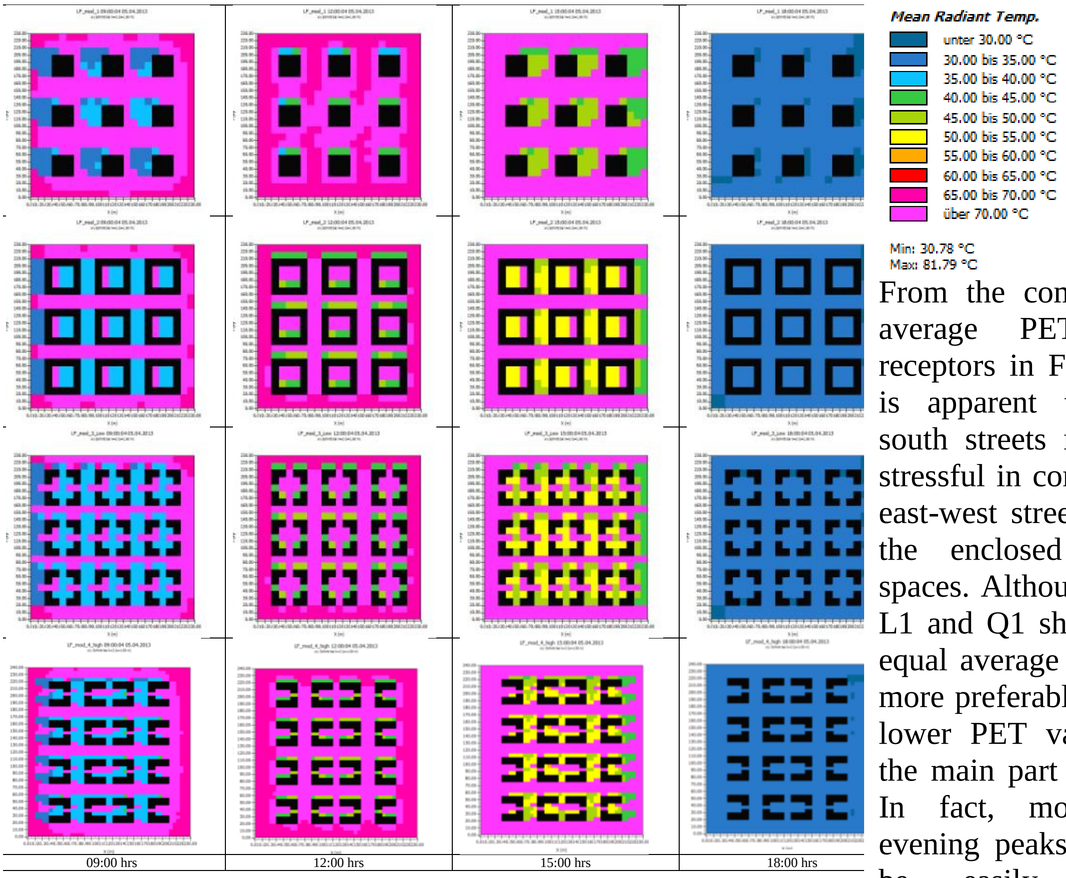


Figure 8.Tmrt across different time periods at different urban types

From the comparison of average PET in all receptors in Figure 10, it is apparent that north-south streets remain less stressful in comparison to east-west streets and also the enclosed courtyard spaces. Although receptor L1 and Q1 shows almost equal average PET, L1 is more preferable due to its lower PET value during the main part of the day. In fact, morning and evening peaks in L1 can be easily overcome through design solutions.

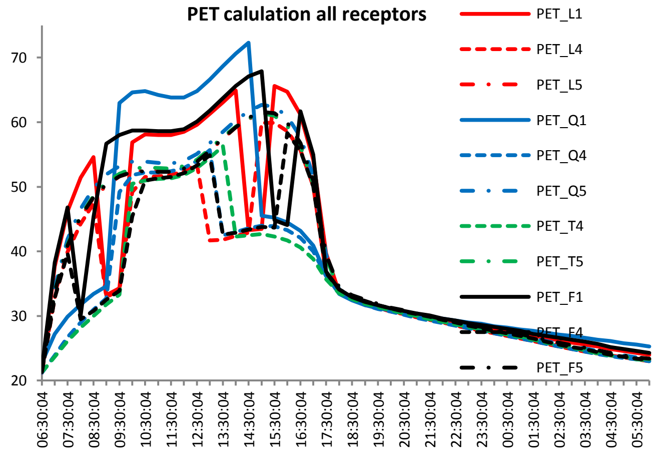


Figure 9. Comparison of PET in all receptors

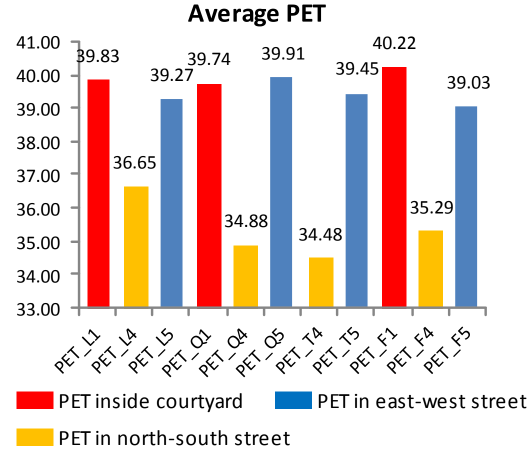


Figure 10. Comparison of average PET in all receptors

Finally, all PET values are found to be extremely high throughout the day well exceeding the comfort range of 28.5^{0}C to 32^0 C. It appears that open-square courtyard offers an outdoor environment that is less stressful during the worst case situation for a hot-humid climate.

Indoor Conditions

Energy Consumption. Heating energy is not a concern in this climate for the maximum period of time of the year; therefore, it has been ignored. In terms of lighting and equipment, all rooms have similar artificial lighting conditions and similar equipments. Daylight is not considered in this study because cooling load is the main concern in such tropical climate condition. Additionally, most of the rooms in all models are in passive zones, except Model 1. Therefore, Lighting energy in Model 1 is assumed to be the highest.

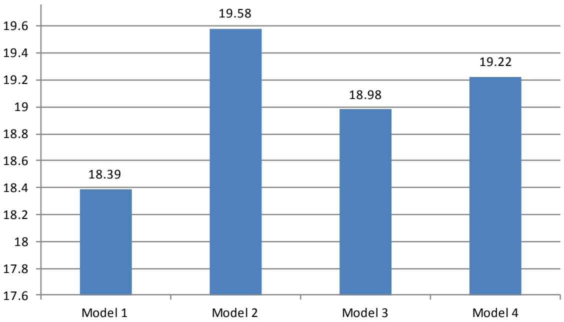


Figure 14. Average of total cooling energy (Kw) in model rooms in different models

In this study, environmental conditions of the passive rooms are only considered. Corner zones have been omitted because they are exposed to environmental variables from different orientations. Otherwise, the impact of a single orientation cannot be clearly understood. Non-passive rooms have also been excluded, because in the tropical hot-humid climate they are considered to become overheated even when outdoor thermal conditions are acceptable.

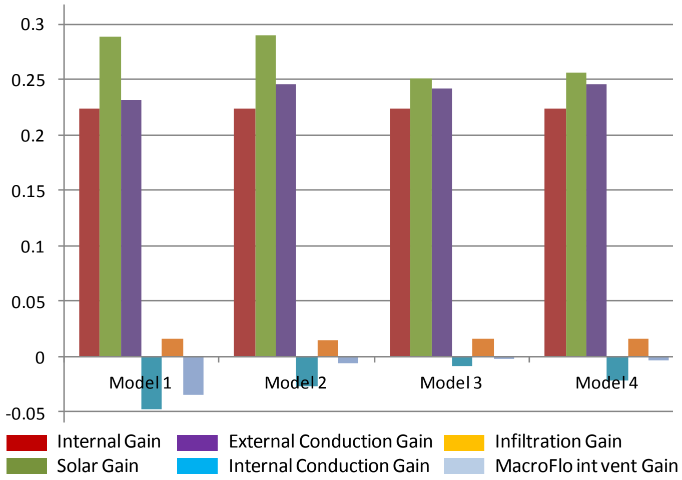


Figure 15. Sensible heat balance in different models

Excluding the corner and non-passive zones, average cooling energy demand in all passive rooms in Model 1 is found to be the lowest (Figure 14). Although solar gain in Model 1 (0.2885 kW) is almost equal to solar gain in Model 2 (0.290175 kW), its cooling load is lowest due to the fact that much of its heat is carried away (through internal conduction loss) to the neighbouring non-passive rooms which are protected from direct solar gain (solar heat gain is zero) (Figure 15). Again in Figure 14, energy performance of Model 2, enclosed courtyard is the poorest. Apparently, this has resulted from higher average solar gain, external conduction gain and lower Macroflo internal ventilation loss in Model 2 (Figure 15). Although Model 2 and Model 3 have similar courtyard sizes and Model 2 has higher site coverage (64%) than Model 3, the former is vulnerable to more solar radiation (and thereby higher external conduction gain) due to its lower height. This indicates shallow courtyards may not be proper for this climate to protect from solar gain.

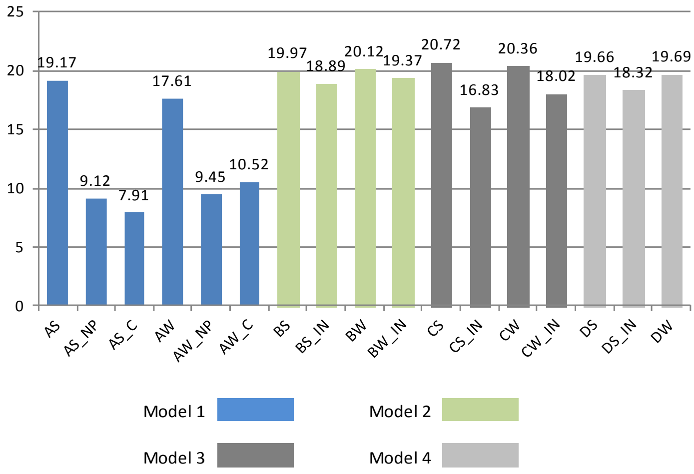


Figure 16. Showing total energy consumption (kwh) in models

Comparison of solar radiation for Model 3 (8 storied) and Model 4(7 Storied) reveals the same fact as solar gain is higher for the latter. Therefore, it appears that, the variation of cooling load is rather a product of height difference rather than an outcome of permeability and orientation of courtyard patterns.

The difference in air-temperature (not shown here) between models is quite insignificant due to the use of internal cooling system. The impact of natural ventilation or permeability of the urban blocks could not be understood for the same reason.

The total cooling load for the experiment day is illustrated by Figure 16. All rooms facing the courtyard have lower cooling load than its corresponding room facing the street. This phenomenon is most prominent in Model 3. This indicates the presence of mutual shading in court-yard models are able to cut down the energy consumption to some extent.

Conclusion

In this study, the exploration of conventional yet representative urban forms in terms of outdoor and indoor conditions has led to the understanding that all of them have merits and demerits. Therefore, from a designer's perspective it would be prudent to select the best aspects from every pattern and combine them together in any future application. For example, enclosed-courtyard model has greater shade and open-square-courtyard has greater air-flow. If the amount of shade could be increased in the latter through design interventions, its performance would be more favourable for outdoor thermal comfort.

Both shading and air-flow are important parameters for outdoor thermal comfort in a hot-humid climate. Although, presence of shading has been proved to have far greater influence than the presence of wind; combining both have resulted in better thermal comfort, as can be seen in the open-square courtyard model. While mutual shading has been achieved by creating courtyard spaces, greater air-flow is achieved by enhancing permeability of the courtyards.

Besides mutual shading, the other element that plays great role in determining the amount of shade is orientation. It is evident from the study that north-south streets offer better comfort in comparison to east-west streets and also the courtyard spaces. Again, square courtyard performs better than the east-west oriented courtyard, since the latter is mostly exposed to solar radiation throughout the day.

Comparing the cooling energy load in all models, all rooms along the courtyards are found to consume lower energy than the corresponding rooms facing the streets, thus signifying the benefit of mutual shading which is achieved here through courtyard spaces. However, this difference is more apparent in south-facing rooms and for models with greater height. This show, courtyards can be applicable for hot-humid climate as well. Higher energy performance of the non-passive zones has been ignored in this study because of their higher chance to overheating in a less extreme situation.

It can be deducted that, by applying sufficient permeability through urban blocks can produce better results for outdoor conditions in courtyard arrangements in hot-humid climate. However, its application for improving indoor conditions is not fully understood due to the use of cooling system. Further study is necessary for naturally ventilated conditions.

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