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Impact of urban morphology on Microclimatic conditions and outdoor thermal comfort – A study in mixed residential neighbourhood of Chennai, India.

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1. Abstract

The urban built geometry alters the microclimate significantly which in turn affects the outdoor thermal comfort. The outdoor thermal comfort depends on the ability of the materials to absorb solar radiation (albedo) and the geometrical arrangement of the buildings and its morphology. The aim of this study is to investigate the influence of the built geometry and its morphology on the outdoor thermal environment in a mixed residential neighborhood in the hot humid city of Chennai. The study is twofold. Firstly, the impact of built geometry on the microclimatic conditions was assessed through field measurements and secondly a questionnaire survey on thermal sensation was conducted to study the subjective response of the users to the outdoor thermal environment. The field measurements included the monitoring of meteorological parameters such as air temperature Ta, relative humidity RH, wind speed v and mean radiant temperature Tmrt. Outdoor thermal comfort conditions were assessed through the physiologically equivalent temperature (PET) index, at different built morphology. The influence of various built parameters such as Sky view factor (SVF), street geometry/ aspect ratio, building materials, green cover, etc., on microclimatic conditions and the thermal sensation were assessed. This study also attempts to identify the appropriate urban morphology to improve pedestrian comfort conditions in the hot humid city of Chennai.

2. Introduction

Urban areas expand its boundaries persistently due to the increase in population growth, economic and infrastructural development thus altering the urban morphology. Urban morphology typically defined by the density of buildings, built geometry, percentage of vegetation cover and characteristics of ground cover. In particular, the replacement of the natural earth's surface by hard impervious layer and the properties of the dense construction materials alter the microclimate significantly. The outdoor thermal comfort in an urban neighbourhood depends on the ability of the materials to absorb solar radiation (albedo), the geometrical arrangement of buildings and the sky view factor. Street geometry is the height to width ratio (H/W) of the street and a typical street canyon is described by its cross-section (Oke 1988, Arnfield 1990). Generally, development regulations of a city dictate the urban built geometry which is primarily based on the economic growth pattern and not on the human comfort conditions, thereby converting the outdoor thermal environments very stressful. The dense construction materials increases the surface temperature, the building geometry traps the incident solar radiation, the hard impervious pavements, roads and parking lots increases the surface runoff of water and the reduced vegetation increases the air temperatures at the microclimate level, affecting the outdoor thermal comfort. In developing countries, most of the urban poor spend their time outdoors thus highlighting the need to improve outdoor comfort conditions. Also, improving outdoor comfort conditions can enhance pedestrian movement in urban neighbourhoods. Therefore, the aim of the present study is to investigate the influence of built geometry and its morphology on the outdoor thermal environment in a mixed residential neighborhood in the hot humid city of Chennai. According to Oke (1984, 1988), findings of urban climatology has a significant role in urban planning and design, hence this study attempts to identify the appropriate urban morphology in improving pedestrian comfort conditions.

3. Background Literature

Urban built form alters the thermal environment significantly at the micro-scale and the thermal climate at the canopy layer shows an intimate relationship with street geometry which mostly depends on the characteristics of the individual site (Oke 1976). Aspect ratio and orientation with reference to solar radiation influences the timing and magnitude of the thermal regime of urban surfaces (Nunez and Oke 1977, Ali-Toudert and Mayer 2006). Rate of cooling at the street level depends on two major urban parameters: height to width ratio (H/W) and sky view factor (SVF) (Oke 1981). Also, Arnfield (1990) found that the canyon geometry is the predominant factor and the rate of cooling in different street geometries are enhanced by the thermal properties of the materials.

Ahmed (1994) found that in summer, increase in H/W ratio reduced air temperatures by 4.5K. Shashua-Bar (2006) indicated that envelope ratio (overall geometry factor) determines the thermal environment of built form, vegetation and colonnades, in streets and courtyards. Outdoor thermal comfort at different sites is significantly influenced by the varying street geometries in cities and Johansson and Emmanuel (2006) found a difference of 7^{o}C between sites in Colombo, Srilanka. Amirtham et al (2009) investigated the land cover changes due to urbanization in the city of Chennai from 1991 to 2000 and found a significant increase in hot spots in the city mainly attributed to the increase in the urban built up.

The dynamic climatic conditions outdoors proves it difficult to quantify the human thermal sensation which depends on four environmental parameters (air temperature, humidity, wind speed and radiation) and two personal parameters (clothing and activity levels). Thermal comfort conditions are affected by the absorption of solar radiation and the exchange of long wave radiation. The thermal comfort indices derived using the energy balance model highlight the significance of radiation fluxes on humans (Mayer and Hoppe 1987, Jendritzky et al 1990, Mayer 1993). The PMV index initially developed for indoor conditions was later extended to outdoor conditions through the Klima Michel model which considers the complex radiations outdoors (Jendritzky et al 1990). The PMV model does not consider the thermo physiological regulatory processes, and the same has been included in the “Munich energy balance model for individuals” (MEMI) (Hoppe 1993) which calculates the Physiologically Equivalent Temperature (PET) based on the MEMI model. PET is a universal thermal comfort index used in the calculation of outdoor comfort conditions (Jendritzky et al 1990, Matzarakis et al 1999).

Earliest study on outdoor thermal comfort conditions by Matzarakis and Mayer (1998) identified that the thermal stress levels of human depend on shading and clothing. In Beni-Isguen, Algeria, Ali-Toudert et al (2005) identified the role of building materials in determining the heat stress and also found that sheltered urban sites were comfortable when compared to unobstructed sites exposed to direct solar radiation. Differential shading of streets due to varying street geometry in complex urban environments of Szeged, Hungary, resulted in 15^{o}C to 20^{o}C difference in PET index (Gulyas et al 2006). The MRT and PET values can be significantly reduced by the shading effects of trees in urban areas (Mayer et al 2009). Also lower SVF can improve the outdoor thermal comfort significantly (Lin et al 2010). Though solar access has a strong relationship with SVF, Kruger et al (2011) identified that wind speed plays a major role in the relationship between MRT and SVF. While improving the comfort conditions at street level, Hwang et al (2011) insisted that seasonal shading effects should be considered. Amirtham et al (2011) found that the differential heating due to the varying aspect ratios of the street canyons resulted in different micro-climatic conditions in the coastal city of Chennai and found that medium rise medium density built form can improve the outdoor comfort conditions significantly. In Singapore, Yang et al (2013) found that combining higher and lower densities in urban areas resulted in reduced incoming solar radiation with an improved outdoor thermal comfort and also identified higher tolerance limit for outdoors when compared to indoors. Also, sun and thermal conditions influenced the behavioural adaptations in urban open spaces (Lin et al 2013). Studies reveal that significant improvement in outdoor comfort conditions could be achieved by appropriate urban design and shading by planners and architects. Therefore, this study aims to analyze the impact of urban morphology on outdoor thermal comfort conditions in the hot humid city of Chennai and attempts to arrive at appropriate aspect ratio for improved pedestrian comfort conditions.

4. Area of Study

Chennai Metropolis lies between 12°50’49”N and 13°17’24” N latitude and 79°59’53”E and 80°20’12” E longitude, along the south eastern coast of India, representing the hot humid type of tropical climate. It is located on a flat coastal plain with an average altitude of 6m above sea level. The mean night time and daytime temperatures ranges from 28°C to 37°C, and 20°C to 28°C during summer and winter respectively, resulting in low diurnal temperature ranges, below 10°C. The average monthly relative humidity ranges from 63% (June) to 80% (November) and the vapour pressure varies between 22.6hpa and 32hpa.

Thiyagaraya Nagar, a mixed residential neighbourhood, once planned as a residential neighbourhood, with an 8 acre central park (Panagal park); has now developed into one of the busiest shopping districts of Chennai with shopping activities aligned along all its major arterial roads. During weekends the floating population of the neighbourhood reaches to about 5,00,000 people with majority of them being pedestrians traversing in and around the central park. Apart from the central park, the neighbourhood also houses two other smaller parks (Natesan Park and Jeeva Park) with one neighbourhood playground. Nine locations were selected in the neighbourhood and the urban parameters that were considered in the site selection include the amount of vegetation, percentage of urban built-up in terms of buildings, roads and pavements, and canyon geometry (H/W ratio). Figure 1 and 2 shows the location of the neighbourhood in Chennai Metropolis and nine measurement locations. Table 1 shows the characteristics of the selected locations in Thiyagaraya Nagar neighbourhood of Chennai Metropolis.

Fig. 1 Location of neighbourhood in Chennai Metropolis and the nine measurement locations.

5. Methodology

The impact of urban morphology on outdoor thermal comfort conditions are evaluated across different canyon geometry by means of physiologically equivalent temperature (PET) – most commonly used outdoor thermal comfort index (Matzarakis et al 1999, Emmanuel 2005, Johansson 2006). The present study evaluates the outdoor thermal comfort through field surveys and questionnaire surveys. The field measurements included the monitoring of meteorological parameters such as air temperature T_a, relative humidity RH and wind speed v. Air temperature and relative humidity data were measured continuously every half an hour using HOBO dataloggers (HOBO U20 Temp/RH) in the selected measurement locations on a typical winter day (30th January 2013). Wind speed were measured using hand held Anemometer and the cloud cover data from the Nungambakkam Meteorological station. The RayMan Pro model (Matzarakis et al 2007, 2010) has been used to calculate the Mean radiant temperature T_{mrt} and Physiologically Equivalent Temperatures (PET). The 200m X 200m grid of the measurement locations, aspect ratio and the SVF are shown in Table 1. Also, a questionnaire survey on thermal sensation in the measurement locations was conducted to study the subjective response of pedestrians with respect to outdoor thermal environment. The subjective response of the respondents and the PET Index were compared to identify the appropriate built geometry for thermally comfortable environment.

6. Findings and Discussions

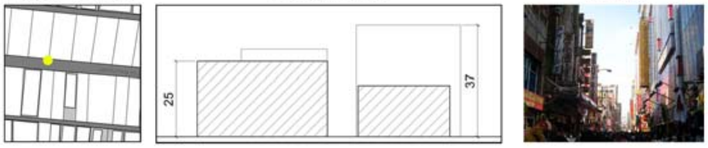
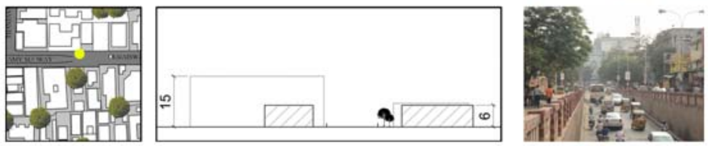
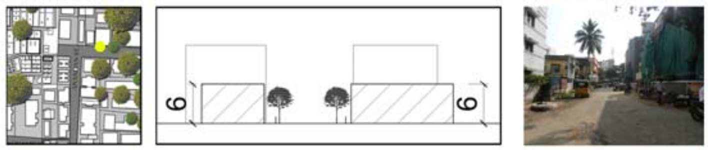
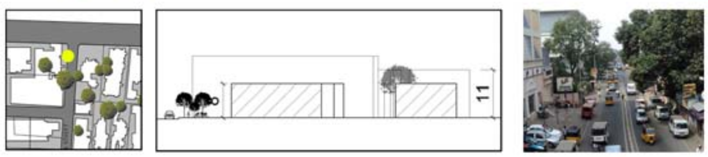
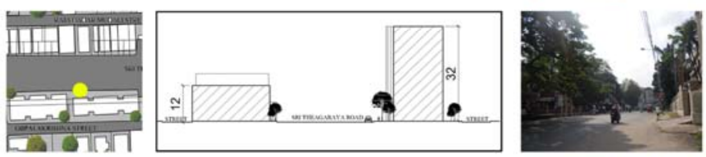
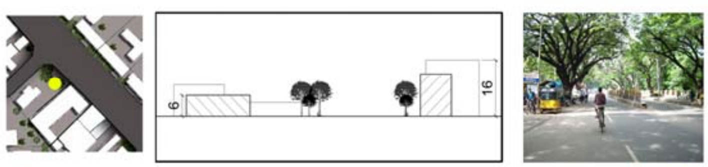
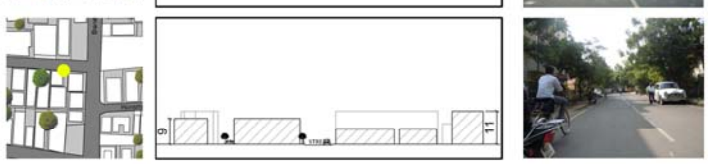
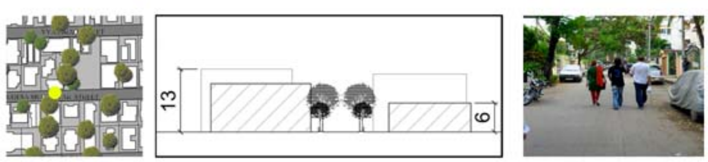
The influence of urban morphology on outdoor thermal comfort conditions were analyzed with respect to parameters such as built-up density, aspect ratio (H/W ratio) and percentage of vegetation / ground cover. The air temperature and PET variations at nine measurement locations are shown in Figure 2. The atmospheric conditions altered by the urban functions and built form results in the modification of micro-climate which depends on various parameters such as cloud cover, time and day of the year, aspect ratio, density of buildings and properties of dense building materials (Mayer et al 2009).

6.1 Air Temperature, MRT and PET Analysis

The air temperature, MRT and PET were analyzed with reference to aspect ratio and percentage of vegetation / ground cover of measurement locations.

Air Temperature Variations: Location 1 was found to have the highest built-up density with an aspect ratio of 3.1. And the aspect ratios were around 1 at Locations 3, 5, 8 & 9 with medium built-up density. Location 4 was found to have the least aspect ratio with 0.36 abutting the central park. Maximum temperatures were recorded at 14.00hrs in almost all the locations with maximum of 31.7^{o}C at location 1 and temperature variations between the different locations ranged upto 3.2^{o}C. The maximum temperature recorded at location 1 is due to its E-W orientation and the narrow street geometry. At 14.00hrs locations 3, 5, 6, 8 & 9 recorded almost similar temperatures. Variations in air temperatures gradually increased from 8.00hrs to 14.00hrs with a difference of 2.1^{o}C to 3.2^{o}C between locations respectively. Minimum Temperatures were recorded at 8.00hrs in almost all the locations except location 5 which recorded the minimum temperature at 7.00 hrs. During nighttime the Sky view factor (SVF) contributed to the increased air temperatures at the canyon level with the maximum temperature recorded at location 1 followed by location 5 with SVF of 0.220 and 0.424 respectively as the heat stored by the building materials during daytime could not be reradiated back to the atmosphere owing to its lesser SVF.

Table. 1 Characteristics of the measurement location in Thiyagaraya Nagar neighbourhood of Chennai Metropolis.

	LOCATION	SECTION	VIEW	SVF	H/W
1				0.220	3.10
2				0.783	0.70
3				0.870	0.90
4				0.636	0.36
5				0.424	0.95
6				0.567	0.73
7				0.937	0.44
8				0.770	1.10
9				0.754	1.05

The diurnal variation between sites varied between 7°C at location 1 with an aspect ratio of 3.1 to 3.3°C at location 4 with an aspect ratio of 0.36. Location 4 abutting the central park with lots of dense vegetation reduced the daytime air temperatures due to evapotranspiration resulting in the reduced diurnal variation whereas at location 1 the absence of vegetation cover and the glazed façade resulted in the increase of daytime air temperatures.

MRT and PET variations: The study revealed a significant relationship between solar radiation and wind speed on MRT and PET temperatures. Maximum MRT and PET temperatures were recorded at 11.00hrs instead of 14.00hrs. The higher wind speeds between 12.00hrs and 13.00hrs reduced the MRT and PET values significantly. The maximum temperature difference between PET and air temperatures were 4.6°C and MRT and air temperatures were 18.7°C. The duration of sunshine between 6.00hrs and 18.00hrs increased the MRT and PET significantly. Even though the air temperatures were within the comfortable range, the intense solar radiation resulted in elevating the discomfort in MRT and PET values.

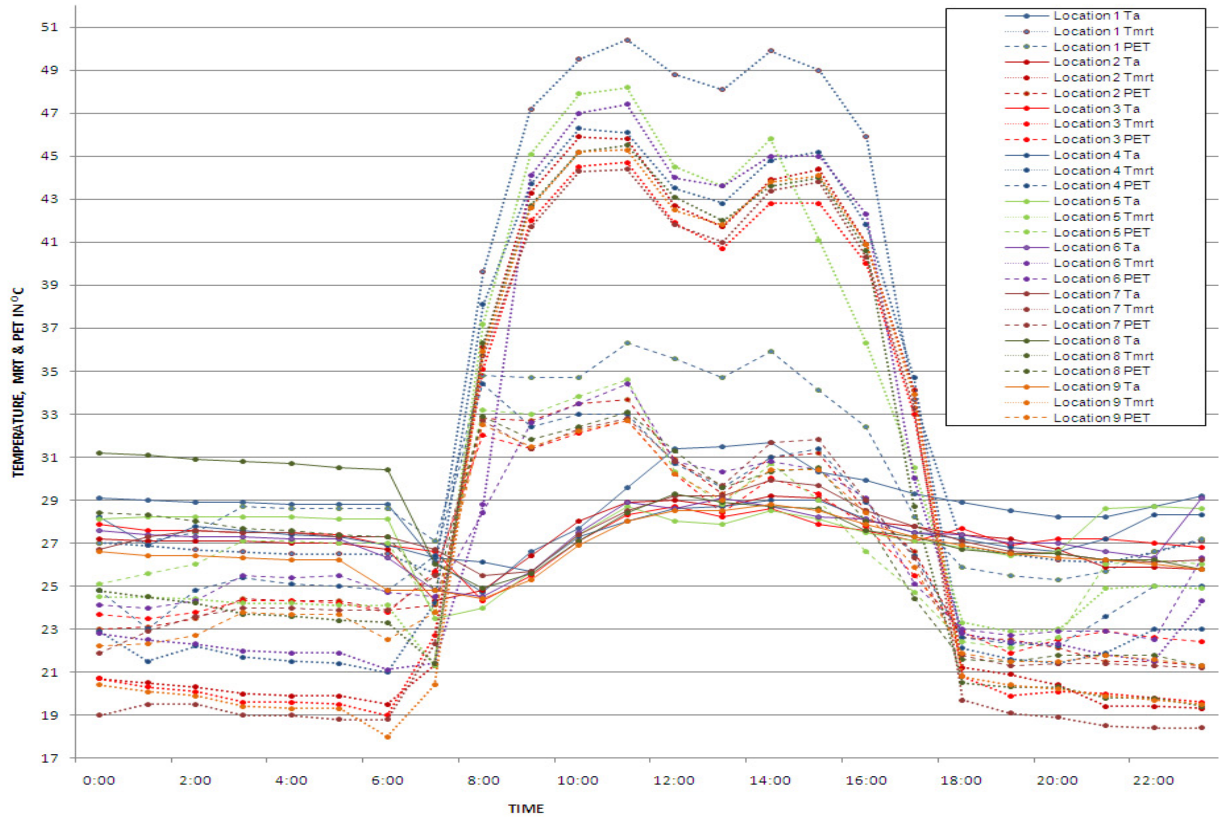


Fig. 2 Air Temperature, MRT and PET variations in the nine measurement locations.

Location 1 experienced the maximum temperature, MRT and PET values at 11.00hrs owing to its E-W orientation of the street, H/W ratio of 3.1, SVF of 0.220 and absence of vegetation. Also the congested pedestrian flow, absence of shading added to the discomfort. Locations 3, 7 & 9 recorded the least MRT and PET during 11.00hrs owing to the shading of trees whereas location 4 experienced higher temperatures even though abutting the central park. This is due to the fact that the location 4 is in the intersection of E_W and N_S street and also due to the wider aspect ratio of 0.36. Also the existence of Urban Heat Island in the neighbourhood is clearly evident during the calm winter night especially between 4.00hrs and 8.00hrs and an UHI intensity of 2.5^{o}C to 4.7^{o}C exists in the neighbourhood.

At 11.00hrs, maximum MRT of 50.4^{o}C and minimum MRT of 44.4^{o}C were recorded at Location 1 & 9 respectively; and maximum PET of 36.3^{o}C and minimum PET of 32.7^{o}C were recorded at location 1 & 9 respectively. At 6.00hrs both MRT and PET recorded minimum temperatures ranging from 18^{o}C to 22.5^{o}C.

6.2 Questionnaire Survey

The questionnaire survey revealed that the respondents experienced heat stress during daytime at all locations. The thermal sensation at locations 3, 7 & 9 were comfortable due to the shading of trees. Location 4 abutting the central park was almost tolerable but was not as comfortable as location 3, 7 & 9 as the park acts as a traffic island and the anthropogenic heat emitted by the vehicles added to the discomfort. The thermal sensation of pedestrians at location 1 was too warm during daytime as the heat radiated from the glazed surfaces of abutting buildings added to the discomfort significantly. Also the internal shading of buildings were absent during daytime due to its E-W orientation. The respondents at locations 2, 5, 6 & 8 complained of heat stress during forenoon when compared to the afternoons. This is mainly because of the higher wind speeds experienced in the afternoons increased the comfort levels of the pedestrians. The study revealed that shading of pedestrians at the street level especially in wider street geometries increased the comfort conditions significantly. Also the pedestrian stretches at location 1 would have been comfortable if oriented in the N-S orientation and the location of parks should be away from the traffic movement for better comfort conditions.

7. Conclusion

The air temperature, MRT and PET trends in the neighbourhood revealed that the nights were comfortable when compared to day. During daytime, all the streets were uncomfortably hot with the MRT and PET values well above the upper limit of the comfort zone. As the daytime comfort was found to have a significant correlation with the street geometry (SVF), presence of vegetation and orientation, the study indicates the significance of improving the daytime comfort in the neighbourhood, by stipulating appropriate built geometry and orientation in the new neighbourhoods. Also if the concept of shading by trees in the wider streets can be adopted in the existing urban morphology, it can improve the comfort conditions to a significant level.

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