Effect of Courtyard on Comfort - Study of thermal performance characteristics of courtyards in hot and humid climate

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Abstract: Courtyards are building elements that originated from the hot dry regions, are amongst the oldest architecture footprint that have been used in buildings by human and now has gained wide acceptance in various parts of the world. The geometry of the courtyard form affects considerably the shadows produced on the building envelope, and consequently the received solar radiations and the cooling and heating loads of the building. In recent years, there has been a growing interest in the design of courtyards for the microclimatic enhancement of outdoor spaces. However, there is still little knowledge regarding the thermal performance characteristics of courtyards, particularly in hot and humid climates. This study reviews and evaluates the available literature on courtyards for providing thermally comfortable outdoor spaces and analyse and discuss the results of a simulation study performed according to different design configurations and scenarios of orientations and use of vegetation in an enclosed courtyard space to optimize courtyard orientation and acceptable vegetation densities for maximum thermal comfort.

The software ENVI-met 4.4, a three-dimensional fluid dynamics microclimate software is used as a tool to carry out the parametric studies for simulating the outdoor thermal performance of an enclosed courtyard in the hot and humid climate of Tiruchirappalli, India, for an identified hot day and building occupancy period. This software provides the platform to model the surface-plant-air interactions in urban spaces with a typical resolution from 0.5 to 10 m in space and 1 to 10 s in time. ENVI-met requires detailed inputs related to the meteorological data, building, vegetation and soil characteristics. Five different permutations of vegetation densities and subsequently 10 orientations of courtyard are simulated for outdoor thermal performance and comfort. Comparison of the simulated results is done on the basis of shadow analysis, air temperature, wind speed, relative humidity and mean radiant temperature. Also, the Physiologically Equivalent Temperature (PET) index allowed to further explore the thermal comfort conditions of the courtyard space. As a result, guidelines are proposed to optimize the design of courtyards based on their vegetation densities and orientation towards enhancing their thermal performance characteristics.

It is important to take into consideration the orientation and location during the early design stage of courtyards. The results of the study suggest that a major change in the thermal performance of the courtyard can be achieved by properly orienting the building and the courtyard to achieve maximum internal shading, better wind speeds and controlling humidity. Even though increasing the use of trees in courtyards directly results in an increased level of relative humidity inside the courtyard space and reduction in wind movement, it was observed that an abundance in the amount of vegetation in the courtyard can help achieve an acceptable level of thermal comfort in the region and may be used by its users for a larger proportion of courtyard area and duration of occupancy period. Finally, this paper...
stresses that only well-designed courtyards and landscapes may represent a viable option for sustainable built environments.

Keywords: courtyard, microclimate modifier, mean radiant temperature, physiologically equivalent temperature

1. Introduction

Meteorological and climatic conditions of urban areas constitute a relevant issue for urban design and urban studies, as they affect human thermal comfort both outdoors and indoors, influencing the appreciation and use of open spaces and, indirectly, the energy consumption of buildings for heating, cooling and ventilation. Urban design itself plays an important role in determining these conditions, which is generally not fully considered by designers. To address this lack of awareness, there is a need for an interdisciplinary approach of architecture and urban climatology, able to investigate the long-term interrelation of climate, thermal comfort and city structure on an operative level, going beyond both empirical, inferential studies on single urban areas or single seasons and abstract analysis concentrated on physical and atmospheric processes.

The climate of individual cities depends mainly on macroscale and mesoscale topographical and physical factors such as geographical position, orography, water cycle, etc. and it is susceptible to relevant variations for limited temporal and spatial changes (Kuttler, 2000). Within the vertical scale of Urban Canopy Layer (UCL), which constitutes the lower part of the roughness sub-level, (approximately from the ground to the rooftops of buildings), the effect of urban design factors on microclimate becomes substantial and it strongly affects thermal comfort (Oke, 2004).

Urban geometry (dimension of buildings and spaces between them), urban cover (materials of built and unbuilt surfaces), urban fabric (construction and vegetation) can modify short and long radiation fluxes, air movements and evapotranspiration (Martinelli et al., 2017). Urban geometry and urban fabric define typology classification, which provides a simplified description of urban structures for urban design (Martin & March, 1972). By removing the complexities of real urban zones, these generic forms allow a systematic assessment of the environmental behaviour of city shape and have proven effective in linking design strategies and thermal comfort (Ratti, 2003).

The courtyard typology constitutes a traditional dwelling in many Asian, North African, South American and European countries for buildings. A courtyard is defined as a multi-storey building centred on an open space, normally accessed from the street. This open space acts as a climate modifier both for indoor and outdoor conditions (Givoni, 1998), and provides a more protected microclimate compared with the archetypical block and pavilion typologies. Conducting research on sustainable design strategies to decrease energy demand is essential. In this regard, the construction of courtyards may be an effective sustainable strategy to control the microclimate and the energy consumption of buildings.

1.1. Courtyard

The Cambridge Dictionary defines a courtyard as “An area of flat ground outside that is partly or completely surrounded by the walls of a building.” The amount of shadow changes in the courtyard during the day, and consequently, temperature differences occur between surfaces and causes a heat
transfer through convection between the surfaces and the air in the indoor and outdoor spaces of the courtyard. A fraction of the heat is stored in the thermal mass of the courtyard, which is released at night. The remaining part of the heat transfers through conduction, and natural ventilation occurs through the sky over the courtyard (Oktay, 2002).

In the late 1960s, Martin and March (1975) studied six urban block forms at Cambridge University. Their detailed study of the built potential and daylight amount concluded that the courtyard creates optimum land use. Ratti et al. (2003) studied three urban blocks based on Martin and March in a hot and arid climate. They calculated the surface to volume proportion, sky view factor, daylight, and shade amount and further concluded that the courtyard layout had the best performance among the various building forms.

The implementation of courtyards has always been regarded as a suitable design to offer privacy, comfort, and minimum energy usage. Furthermore, courtyards provide a good amount of daylight, natural ventilation, and thermal performance. Meir (1995, 2000) also believes that applying courtyard structures as microclimatic modifiers has been considered during the last four decades, particularly in hot and arid weather. Additionally, research in the United Arab Emirates showed that the annual energy consumption of an optimized courtyard is 11.16% lower than that of conventional building forms (Masri et al., 2012).

Many studies with different methods examined the climatic aspects of courtyards. Due to complex interactions between the microclimatic and thermal functions of the courtyard, simultaneous simulation of the thermal conditions of indoor and outdoor spaces is inevitable. The interactions between the building and its surroundings occur at three levels: the building, neighbourhood, and urban levels. The integrative approach of indoor and outdoor thermal conditions has been used before; Yi and Peng (2014) demonstrated the interaction between building indoor thermal performance and outdoor microclimates using three simulation software programs at three microclimate levels:

- CCWorldWeatherGen at the city level,
- ENVImet at the neighbourhood level, and
- DesignBuilder at the building level.

2. Parametric simulations of courtyards

Parametric simulations for analysing the thermal effects of courtyards in the hot and humid climate of Tiruchirappalli have been carried out. Tiruchirappalli is a city in India, a South-Asian country encompassing a tropical area and is situated almost at the geographic centre of the state of Tamil Nadu near the equator (10°48′18″N 78°41′08″E) and has a hot and humid climate. As such, when designing outdoor spaces in this area special attention needs to be paid to the impacts of solar radiation and possible ventilation. Annual mean air temperature for Tiruchirappalli is approximately 28.9 °C (84.0 °F) and monthly average temperatures ranging between 25 °C (77 °F) and 32 °C (90 °F), making the city the hottest in the state. The warmest months are from April to June, when the city experiences frequent dust storms. The high temperatures and humidity in the city have been attributed to the presence of two rivers, Kaveri and Kollidam, and the absence of greenery around the city. The relative mean humidity ranges between 40% and 80%. The days are extremely warm; evenings are cooler because of cold winds that blow from the south-east. From June to September, the city experiences a moderate climate tempered by heavy rain and thundershowers. Rainfall is heaviest between October and
December because of the north-east monsoon winds, and from December to February the climate is cool and moist. The average annual rainfall is 841.9 mm (33.15 in). Fog and dew are rare and occur only during the winter season.

2.1. Overview of the methodology

The thermal performance characteristics of courtyards were analysed according to the following design parameters: location and orientation, occupancy period and presence of vegetation. ENVImet 4.0, a three-dimensional fluid dynamics microclimate software was used to carry out the parametric studies. This software provides the platform to model the surface-plant-air interactions in urban spaces to calculate microclimatic parameters like wind, surface temperature, mean radiant temperature, etc. It is designed basically for micro-scale simulation with a uniform resolution (0.5 to 10m) in the horizontal surface and 10 s in time. It includes the key modelling inputs, initial climatic parameters, building structure including site location, plant type and soil type and thermal properties.

In order to interpret properly the simulation outputs, it is essential to consider the assumptions behind ENVImet as shown in the Table 1.

Table 1. Assumptions for simulation in ENVImet

<table>
<thead>
<tr>
<th>Assumptions in ENVImet</th>
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<tbody>
<tr>
<td>• Flat ground</td>
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<td>• Box shaped buildings</td>
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<tr>
<td>• Cubic grid with horizontal resolution of 1 m. Higher resolution is enabled only for the vertical axis</td>
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<tr>
<td>• Empirical initial boundary conditions, found by trial and error, in order to get good agreement with average measurement data</td>
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<tr>
<td>• Constant wind profile during all simulation times</td>
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<tr>
<td>• Buildings have constant indoor temperature and no heat storage</td>
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<tr>
<td>• 1D soil model considering a five-level profile of humidity and temperature</td>
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<tr>
<td>• Vegetation model considering the photosynthesis rate, the CO2 demand, and the state of the stomata, the interaction of humidity and radiation in soil and air</td>
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The study focuses on simulation of air temperature, mean radiant temperature and subsequently physiologically equivalent temperature to evaluate the outdoor thermal comfort conditions of courtyards based on different design configurations

2.2. Selection of a typical day

Based on the Indian Meteorological Department report, Tiruchirappalli is generally exposed to variable winds. Since the impact of wind on the thermal performance of outdoor spaces can be significant, especially in humid climates, a typical day is selected from the main summer season in the present study. In Tiruchirappalli, the highest monthly global radiation can be found between March and June. Looking into the average climate data, the month of May had the highest records of the global radiation, direct radiation, diffuse radiation, and dry-bulb temperatures. Accordingly, this study selected the day of May 09.
2.3. Characteristics of the site and courtyard model

- The study is being carried out in the Hot and Humid climate of Tiruchirappalli, India.
- The site selected for field study is that of an Institutional building named Lyceum, NIT Trichy, consisting majorly of staffrooms. Figure 1.a, 1.b.
- The said building is of G+2 structure with rectangular landscaped Courtyard and is east – west oriented along the longer axis with entries on East and North facades.
- Building Courtyard is of approx. 14m x 34m and approximate height of 12m divided in 3 floors with corridors running along on all the sides.
- The corridor has a parapet as well as beams on all sides on all the floors.
- Simulation is done using ENVImet 4.4 software for a sample courtyard with simple rectangular shape and dimensions of 14m x 34m, for a stretch of 10 hours based on the average occupancy time period, from 8AM to 6PM on hot design day of MAY 9.
- Adopted Temperature range is 27°C – 38°C
- Adopted Wind speed is 3.7 m/s from East
- Plantation type –
  - 2m high dense hedge and 25cm high grass for vegetation simulation
  - Plantation similar to existing vegetation for orientation simulation
- Static Clothing Insulation is 0.9 Clo
- Metabolic Activity is 1.9 Met

2.4. Validating of the software

Air temperature for the select design day was measured on site using a heat stress meter and also simulated using ENVImet 4.0 and compared for a base model with existing design conditions. After minor adjustments, the comparison shows high levels of correlation demonstrating an acceptable agreement between the predicted values and measured data (Figure 1.c.).

![Figure 1. 1.a. Google map image of the building; 1.b. Existing Vegetation; 1.c. Measured Air Temperature v/s Simulated Air Temperature](image-url)
3. Results and Discussion

The study looked at different courtyard configurations. The courtyards had an area of 452m\(^2\), being 14m width by 34m length and staircase shaft cut out of 6m by 4m, surrounded by a triple story building with the height of 12m which was modelled according to the typical of office characteristics. The results presented in this section are divided into the following subsections: vegetation density (Section 3.1), and courtyard orientation (3.2).

3.1. Effect of vegetation

The study considered the utilization of five different configurations of grass and dense vegetation in the selected courtyard model. It has been established from previous studies that adding landscape, particularly trees, will improve the thermal comfort conditions in courtyard because of the larger shaded areas. The thermal performance of courtyard models with no greeneries, 100% covered by grass, 25% covered by dense vegetation, 50% covered by dense vegetation, and 75% covered by dense vegetation were hence evaluated (Figure 2.) and compared against existing landscape model. The results clearly show that increasing the use of vegetation in courtyards directly results in an increased level of relative humidity.

Using dense vegetation considerably reduces the level of air temperature during the critical time of the day (12 to 16). Nevertheless, it is evident that when the sun is almost above the building and insufficient shading is achieved, the adoption of dense vegetation increases the ambient air temperature as well. Indeed, despite the benefits of vegetation, there could be negative impacts in hot climates due to different reasons: they can reduce the wind speed; and can block the net outgoing long-wave radiations. Looking at the thermal comfort conditions (both MRT and PET, figure 3 & 4), it is inferred that increasing the coverage of dense vegetation generally improves the thermal comfort zones and levels. However, coverage of courtyard ground with grass does not have a significant impact on the thermal comfort. As shown in the figures 5, it is clearly shown that the courtyard with highest coverage of trees (75% dense vegetation) significantly reduces the critical period of thermal discomfort. There is sudden rise after 8am and drop after 4pm of MRT in all the models due to absence of direct solar radiation.
3.2. Effect of Orientation

The study considered the utilization of 10 different configurations of orientation in the selected courtyard model with existing landscape conditions. Each configuration is obtained by rotating the entire model by 10-10 degrees towards south as shown in Figure 5.a. It is important to consider orientations of the building and courtyard during the early design phase as it affects the buildings internal and external comfort to a great extent by controlling the amount of exposed surface to direct solar radiation and wind.

The main difference caused by changing the orientation of the courtyard is in the percentage of area that gets shaded by the building. Results show that the difference occurs only during the early hours and late evenings. During the critical period of the day, the sun is directly on the top and hence there is no
major difference caused in shading because of the change in orientation. Ambient air temperature (Figure 5.c.) and MRT (Figure 6.) for the 20° rotated courtyard is observed to be least during the critical period suggesting maximum airflow inside the courtyard for the simulated wind flow and is highest for 10° rotation at 4PM. But, to get the best orientation configuration, we also need to observe the percentage of area getting exposed to direct radiations and these temperatures and thermal comfort conditions which will finally suggest the usable area of the courtyard during the critical period. As we can see in Figure 7 and on comparing it with Figure 6, we observe that though the 20° rotate courtyard is getting the least of the maximum MRT reached in the courtyard, 80° and 90° rotated courtyards are least exposed to direct radiations and thus maximum MRT reached in each condition, proving the maximum usable area during the critical period. Also, there is variation seen in PET near the entrances, which can relate to greater wind speeds.

![Diagram](image)

Figure 5. (L-R) 5.a. Courtyard orientations; 5.b. % of shaded area; 5.c. Maximum air temperature for all 10 orientations

![Diagram](image)

Figure 6. Minimum and maximum MRT for different orientations of courtyard during peak temperature
4. Conclusion

Outdoor thermal comfort plays an important role in enhancing urban life. Through the literature study we established that courtyards may improve the thermal comfort of outdoor spaces if they are properly designed. Major scientific studies focusing on the thermal behaviour of courtyards are predominantly observed in arid or temperate areas. Nonetheless, evaluating the micro-scale thermal environment in tropical context was considered important. Accordingly, the thermal comfort during the design hot day conditions in the hot and humid tropical context of Tiruchirappalli was studied in this research. Findings present new insights to ameliorate the thermal comfort conditions of the built environment in tropical areas by designing efficient courtyards. According to numerous simulations, effective design options for the integration of courtyards are proposed. As a result, the outdoor thermal comfort in courtyards in the hot and humid climate of Tiruchirappalli can improve through adequate attention to the design configurations. Hence, as many studies present that courtyards are predominantly operative in hot and arid areas, they can also perform in hot and humid climates.

A comparison between the different configurations helps clarify guidelines for future optimization of the thermal performance characteristics of courtyards.

- It is crucial to control the amount of direct solar radiations received by the ground in tropical contexts. In this study, simulations were run in clear sky conditions and as a result, SW direct solar radiations are very high. Hence, it should be noted that the high values of PET belong to a sunny day with clear sky.
- Proper selection of orientation of courtyards can lead to receiving maximized wind with higher speed plus an increased amount of shade during the daytime., hence, it is an important factor for ameliorating the outdoor thermal comfort.
- Use of vegetation such as grass for covering the courtyard provides a limited influence towards improving the thermal comfort compared to the courtyard with bare ground;
- Use of trees in courtyards can enhance the overall thermal comfort and can reduce the unshaded areas having a high level of discomfort. Covering the courtyard with 75% dense vegetation leads
to the highest air temperature decrease. Use of trees in warm climates can have negative effects on air temperature at particular times by blocking wind, reducing the wind velocity, and decreasing the nocturnal cooling.

- Courtyards in the hot and humid climate of Tiruchirappalli can provide a thermally comfortable environment and can be enjoyed only during the early morning hours (8:00 to 10:00) and the evening (17:00 onward). It is important to state that the focus of this research was on the courtyards which are directly open to the sky and fully exposed to solar radiations, and therefore providing high thermal comfort is hard to achieve.

It is also useful to remind some of the limits of the ENVImet software used: Static wind speed and direction throughout the day; building temperature is fixed and identical in all the points of the building for all buildings; similarly, the transmittance and albedo values are fixed and identical for all the superficies of the buildings; finally, anthropogenic heat and mass (included water vapor) fluxes such as traffic or air conditioning are not considered.

This study was limited to the thermal performance characteristics of courtyards; nevertheless, future research is needed to understand the impacts of courtyard on the indoor thermal conditions and energy performance of surrounding buildings.

References


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