Effect of neighbourhood courtyard design on the outdoor thermal comfort in a tropical city

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Abstract. In the tropical city of Ha Tinh (Vietnam), the number of new developed neighbourhoods in the courtyard layout is increasing while the city is experiencing annual severe heat stress. The paper quantitatively analyses, by means of ENVI-Met simulation, the effect of neighbourhood courtyard landscape on the outdoor thermal comfort (OTC) in the tropical city of Ha Tinh (Vietnam). A sample 9-ha residential block was at first experimentally configured with four scenarios of courtyard, including (1) bare grass and perimetry location of high plants, (2) grass ground, fully occupied high trees, (3) water body and perimetry location of high plants, and (4) mixed ground surfaces of water, hard pavement and grass, and partly occupied high trees. The adding of tree canopies to the entire courtyard, consequently sufficient shades, as in case 2, contributes to the better OTC among the chosen scenarios by triggering the reduction of mean radiant temperature (Tmrt) (2.9°C) and physiological equivalent temperature (PET) (3.5°C) at the hottest hours as compared to the original configuration (case 1) during the summer days. Application of perimetry plants with either water (case 1) or bare grass (case 3) results in higher PET though full occupation of water body lowers the air temperature by roughly 1°C. The limited impact on OTC of local water body is counter-intuitive, yet important result to the practice of urban design. The worst OTC was observed in case 4 where almost half of the garden was sun-exposed and intended for hard-paved playground and water body. Increasing shades against solar radiation is the most important measure to deal with intensive heat problem. The study is an essential part of translating academic knowledge on urban climate into interventions on urban design for better climate resilience of neighbourhoods in Vietnam and by extend in other tropical countries.

Keywords: outdoor thermal comfort, ENVI-Met simulation, courtyard landscape, tree coverage, shading

1. Introduction

As of a tropical city in the North Central Vietnam, Ha Tinh is exposed to summer heat stress that occurs on a regular basis [1]. A log of annual heat stress days [2] since 2018 presented an upward trend in length. At the same time, the growth of building stocks is another issue of consideration when it comes to the cooling strategies. The approved city master plan will provide room for more than hundred-
thousands of new buildings of residential functions in existing peri-urban regions [3]. A number of studies provided insights into the strong link between the urban morphology and the outdoor thermal comfort (OTC) under various climates of Mediterranean [4], Moderate [5] and Tropics [6]. A variety of parameters that describe/characterize a neighbourhood morphology were considered, including built density [7], street orientation [8] and open space configuration [9]. An empirical study in Ha Tinh by Ngo et al. [10] proved the real impact of street vegetation on the cooling potential, but its influence of open space typology on OTC was not reported.

Although the local open spaces in form of block courtyards are included in the construction plan of neighbourhoods in Ha Tinh, the consideration of OTC improvement is yet unfortunately included in the phase of conceptualization. The only reference is the obligatory green occupied area in relation to gross area of development. Further studies on the landscape of open spaces for the better OTC are therefore necessary when it comes to the neighbourhood development.

The aim of this paper is to investigate how the configuration of neighbourhood courtyards, i.e. the selection of ground materials and landscape design, affects the OTC over a low-rise residential neighbourhood in sub-urban of Ha Tinh by numerical analysis with ENVI-Met.

2. Materials and methods
For a study on OTC and urban design, CFD-based simulation is a popular and reliable method. Among available tools, ENVI-Met is dependable and appropriate for the study due to the dimension of the neighbourhoods of interest. Previous study of Ngo et al. [11] showed the scientific relevance of ENVI-Met in the tropical climate of Ha Tinh (Vietnam) and concluded on the necessity of further validation on the model. This section describes the area of interest, the setting up of micro-climate simulation and the indices used for the evaluation of OTC. Four configurations of low-rise buildings and courtyards are introduced and examined regarding the OTC level. Details on the study are explained in the subsections.

2.1. The area of interest (AoI)
The study area is a sub-urban neighbourhood located in Thach Dai, a southwest rural district of Ha Tinh city, which is of “Am” climate type (i.e tropical monsoon climate) [12] by following the Koppen-Geiger’s climate characterization. Currently, the area is landscaped by sparsely-built low-rise residential buildings, private gardens and agricultural (mostly rice) fields.
2.2. Model for validation
To evaluate the reliability of ENVI-Met model, a domain that covers a 150x150-m area with spatial resolution of 2x2-m was selected for the computational analysis. The area is now landscaped by sparsely-built low-rise residential buildings, private gardens and agricultural (almost rice) fields.

The computation was performed for the sunny day of August 31st 2020 that is representative of hot weather observed in the summer time of Ha Tinh. As recommended by [11], forcing temperature and relative humidity was retrieved from a rural weather station located nearby the area of interest (~1km) instead of those extracted from inner-city meteorological observation point, which improves the reliability of the calculation.

Based on the historical data retrieved from the city reference weather station, it is found that the SW wind is prevailing in the summer. So, in this research, both the wind speed and wind direction (at 10-m height) were assumed to remain constant at respectively 1.5 m/s and 225 degrees (SW) so that the effect of SW prevailing airflow on the OTC was intensively examined.

| Table 1. Set up for the validating simulation.          |                    |
|--------------------------------------------------------|--------------------|
| Brick                                                 | Tile roof          |
| Thickness (m)                                         | 0.30               |
| Absorption                                            | 0.60               |
| Reflectance/ Albedo                                   | 0.40               |
| Emissivity                                            | 0.90               |
| Wetness (%)                                           | -                  |
| Temperature (°C)                                      | -                  |
| Concrete pavement (light)                             | 0.05               |
| 0.70                                                   |
| 0.30                                                   |
| 0.80                                                   |
| 0.90                                                   |
| -                                                       |
| Soil                                                   |                    |
| (0-20 cm/ 20-50 cm/ 50-200 cm)                         | -                  |
| Thickness (m)                                         |                      |
| Absorption                                            |                      |
| Reflectance/ Albedo                                   |                      |
| Emissivity                                            |                      |
| Wetness (%)                                           |                      |
| Temperature (°C)                                      |                      |
| 25 / 23 / 21                                           | -                  |
| 60 / 70 / 85                                           |                    |

2.3. Model configuration
In the study area of 300x300-m, a grid resolution of 3x3-m was selected, which was relevant to the simulation of OTC. 3D-model of the studied neighbourhood was developed from the original master plan approved by the city of Ha Tinh in 2019. The quarter represents a typical morphology of contemporary residence units that is formed with rows of attached family houses and a playground in the center. All buildings were assumed as 14 meters height, an equivalent height of four stories.

Figure 2. The master plan of the AoI (left) and the sample block of study (right).
The wall and roof structures of the modelled buildings were assigned to brick wall and reinforced concrete in respective order as proposed in the development plan. Concrete pavement grey was selected as the material of pavement, while asphalt covers all the ground of traffic network within the neighbourhood. In the original scenario, the open space is located in the middle of the block and landscaped by bare grass and medium plants (of 15-m) on the edges. Details of the materials and vegetation as simulation inputs are included in Table 2.

2.4. Proposed scenarios
In addition to the base proposal (i.e. case 1), three scenarios onto the design of studied courtyard are introduced by adjusting the amount of tree canopies, grass, water bodies and hard pavement on the ground. The common arrangement and assignment of buildings and external mobility plan are applied in all the considered cases. Details of courtyard configuration are explained in Table 3.

2.5. The metric of OTC
The thermal comfort index Physiological Equivalent Temperature (PET) [13] is used to characterize the OTC. PET is equivalent to the air temperature of a typical indoor setting where the heat balance of the human body is maintained with core while skin temperatures equal to those under the conditions being assessed. PET is a thermal comfort index with the consideration of the following meteorological parameters: Ambient dry-bulb air temperature (Ta), Relative humidity (RH), wind speed (Ws), and Mean radiant temperature (Tmrt). It also takes into account the physical characteristic of the human body: gender, height, activity, and clothing resistance to heat transfer, short-wave albedo and long-wave radiation of the surface affected by the physical surface properties. Since a specific scale has not been yet developed for Vietnam, the study utilized the PET classification identified by Yang et al. [14] as a reference to evaluate thermal comfort conditions of outdoor spaces in hot and humid climate that is comparable to the climate of Vietnam. The BioMet tool [15] was employed to calculate PET from the estimated meteorological parameters including Ta, RH, Ws, and Tmrt and modified personal data for local people in summer of Ha Tinh (i.e. Clo: 0.5; Sum metabolic work: 141.48 W).

Table 2. The model configuration and initialization parameters of the studied cases.

|                     | Wall | Roof | Concrete pavement (light) | Asphalt | Water | Bare grass | Medium plant | Soil (0-20 cm/20-50 cm/50-200 cm) |
|---------------------|------|------|----------------------------|---------|-------|------------|--------------|----------------------------------|
| Thickness (m)       | 0.30 | 0.15 | -                          | -       | -     | -          | -            | -                                |
| Absorption          | 0.70 | 0.70 | 0.20                       | 0.90    | 0.96  | 0.50       | -            | -                                |
| Reflectance         | 0.30 | 0.30 | 0.80                       | 0.10    | 0.04  | 0.50       | -            | -                                |
| Emissivity          | 0.90 | 0.90 | 0.20                       | 0.90    | 0.96  | 0.50       | -            | -                                |
| Wetness (%)         | -    | -    | -                          | -       | -     | -          | 60 / 70 / 85 | -                                |
| Temperature (°C)    | -    | -    | -                          | -       | -     | -          | 25 / 23 / 21 | -                                |
| Height (m)          | -    | -    | -                          | -       | -     | -          | 15           | -                                |
| LAD (m²/m³)         | -    | -    | -                          | -       | -     | -          | 2            | -                                |

2.6. Evaluation of OTC
The design scenarios are analysed in comparison to the original configuration in term of temporal distribution of median air temperature (Ta), wind speed (Ws), mean radiant temperature (Tmrt) and PET. These parameters are analysed at time intervals around 10.00 (hottest time in the morning), 12.00 (noon), 15.00 (hottest time in the afternoon) and 21.00 (latest time of human’s outdoor activities) on the day of simulation i.e. 31st August 2020. All simulation results for thermal perception and thermal comfort refer to a height of 1.5m.
Table 3. The graphical and statistical description of four scenarios of interest.

|            | Case 1 | Case 2 | Case 3 | Case 4 |
|------------|--------|--------|--------|--------|
| Asphalt – Entire domain (%) | ~15    | ~15    | ~15    | ~15    |
| Grass – Entire domain (%)   | ~12    | ~12    | ~2     | ~6     |
| Grass – Courtyard (%)       | 100    | 100    | ~20    | ~45    |
| Water – Entire domain (%)   | 0      | 0      | ~10    | ~3     |
| Water – Courtyard (%)       | 0      | 0      | ~80    | ~35    |
| Tree density (pieces/1000m²) | ~2     | ~4     | ~2     | ~2.5   |
| Hard pavement – Entire domain (%) | ~8 | ~8     | ~8     | ~13    |
| Hard pavement – Courtyard (%)   | 0      | 0      | 0      | ~20    |

3. Results

3.1. Model validation

The reliability of ENVI-MET model is evaluated by comparing the modelled and observed air temperature and relative humidity at the the receptor shown in figure 1. The assessment was also summarized with the mean square error (RMSE) and the mean absolute error (MAE). RMSE is the mean squared difference between predicted and observed values, while MAE is the average magnitude of the errors in a group of predictions considering data directions. The calculation formulas [16] of the two indices are shown as follows:

\[
\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (X_{\text{measure},i} - X_{\text{model},i})^2}{n}} \quad (1)
\]

\[
\text{MAE} = \frac{\sum_{i=1}^{n} |X_{\text{measure},i} - X_{\text{model},i}|}{n} \quad (2)
\]

In the above formulas, \(X_{\text{measure},i}\) means the measured values, \(X_{\text{model},i}\) represents the simulated values, and \(n\) indicates the numbers of obtained data.

In general, the simulated values of air temperature (Ta) were in good agreement, as compared to previous studies [16], [17], with the measurements, with a maximum difference of 1.75°C, while values of measured and simulated relative humidity (RH) showed a maximum difference of 5.81% (Figure 3). The RMSE values were 0.56 °C (air temperature), 2.49% (relative humidity), and those of MAE were 0.41°C (air temperature), 2.11% (relative humidity). The confirmatory experiments indicate that the ENVI-Met model is validated and reliable for the simulation study of the effect of courtyard design.
Figure 3. Hourly evolution of measured and modelled $T_a$ - air temperature (left) and RH - relative humidity (right) on the 31st August 2020.

3.2. The effect of courtyard design
The impact of courtyard design on the OTC is analyzed by investigating the effect of the studied scenarios on $T_a$, $W_s$, $T_{mrt}$ and PET. Output data at 10 border grids (30m) was disregarded to remove the effect of boundary layer.

Figure 4. Spatial variation of $T_a$ at 15:00 (31st August 2020) for the studied scenarios.
Air temperature (Ta). Figure 4 shows the spatial variation of air temperature (Ta, °C) over the whole domain simulation, while Table 4 gives a summary of computational outputs in the four scenarios. The median values of Ta hardly differ during the day and almost equal at 21:00 between the four scenarios. Only a limited change in median Ta between case 1 and 2 can be noticed, where case 2 (trees + grasses) causes average reduction of 0.20°C and 0.40°C at 12:00 and 15:00 respectively in refer to bare grass landscape of the case 1. Local Ta values were increased by maximum 1°C at 15:00 over positions exposed to sun (data shown in figure 4). The temperature outputs indicate the lower temperature over the water body at 15:00 (hottest time of the day) as introduced in cases 3 and 4. This cooling potential can be explained by the evaporation of water and the increase of the latent heat, and this capacity is in positive co-relation with the covered area. However, the full ground cover of water as configured in case 3 does not result in considerable reduction of air temperature over the entire studied neighbourhood, and hardly provides optimal exploitation of a public space.

Wind speed (v). The full placement of trees introduced in case 3 causes the wind speed slightly reduced by approximately 0.2 m/s at all studied time intervals in comparison to the proposals that rely on lower or no amount of high plants. Minor impact on the generation of wind speed by the ground cover is observed from insignificant deviation among three other cases.

Table 4. Median values of Ta, v, Tmrt and PET four all cases at the considered time intervals.

| Parameters | Time intervals | Case 1  | Case 2  | Case 3  | Case 4  |
|------------|----------------|--------|--------|--------|--------|
| Ta         | 10:00          | 32.31  | 32.21  | 31.87  | 32.57  |
|            | 12:00          | 34.82  | 34.58  | 34.12  | 34.59  |
|            | 15:00          | 35.55  | 35.17  | 34.38  | 35.11  |
|            | 21:00          | 27.28  | 27.28  | 27.29  | 27.29  |
| v          | 10:00          | 1.01   | 0.88   | 1.03   | 1.01   |
|            | 12:00          | 0.97   | 0.87   | 1.01   | 0.95   |
|            | 15:00          | 0.96   | 0.85   | 1.00   | 1.00   |
|            | 21:00          | 0.97   | 0.87   | 1.02   | 0.92   |
| Tmrt       | 10:00          | 44.56  | 42.26  | 44.10  | 45.98  |
|            | 12:00          | 51.54  | 48.99  | 52.12  | 53.50  |
|            | 15:00          | 47.78  | 41.40  | 45.56  | 46.54  |
|            | 21:00          | 21.28  | 21.30  | 21.41  | 21.52  |
| PET        | 10:00          | 39.20  | 35.00  | 40.56  | 38.03  |
|            | 12:00          | 43.30  | 39.90  | 43.00  | 42.89  |
|            | 15:00          | 42.60  | 38.50  | 42.00  | 42.10  |
|            | 21:00          | 22.81  | 22.82  | 22.86  | 22.90  |

Mean radiant temperature (Tmrt, °C) values are strongly affected by the courtyard design i.e the presence of tree canopies for shades but hardly differ from the choice of ground materials. For case 2, the presence of shadow for the same time interval lowered the shortwave radiation reaching the ground and thus the rise of ground surface temperature was significantly lower than other scenarios. The increased amount of unshaded hard ground surface (concrete pavement light), in case 4, can be blamed for the rise of Tmrt due to its high absorption of intense incident solar radiation, while shadowed surfaces are always cooler. In general, the Tmrt tended to get higher in all scenarios from 10:00 to 12:00, as the sun rises and generates greater amount of solar radiation heating the ground, and is lowered when the afternoon is approaching.
PET. Figure 5 illustrates the distribution of the PET index values, at time interval around 15:00. During daytime, PET values followed the patterns of Tmrt. Extreme heat stress (very hot) occurred especially along the sun-exposed region, i.e. bare grass (case 1), water (case 3) and playground (case 4) where high openness is captured, with PET values reaching up to approximately 56 °C. Trees and shadow provided in case 3 from urban structures triggered a significant reduction in PET. This index ranged between 35 and 41°C in shaded areas and not more than 42 °C during the hottest part of the day.

Although water provides a slightly better air temperature (cases 3 and 4), it does not contribute to the mitigation of extreme heat problem at noon and in the afternoon at 15:00 due to the absence of sun-protection. Only significant reduction of PET is observed in case 2, which moves PET from very hot (>42°C) to warm and hot sectors (34 - 42°C). At a given point (marked in yellow as shown in figure 5), the introduction of shades by tree canopies may result in a decrease by almost 15.00°C in PET, and therefore makes an effective shelter against excessive amount of radiation. Concrete pavement may cause higher PET (up to 2.00°C) compared to cases 1 and 3 where bare grass and water fully cover the ground due to strong absorption that is related to the high Tmrt during the hottest moment.

4. Discussion
The analysis of the simulation outputs revealed that during daytime, the extreme heat stress of a hot day in Ha Tinh become significantly lower at shaded spaces. In the present study, as seen in the results, heat stress was more frequent and intense in the sun exposed areas. Thus, providing shades by trees in these areas can be the most important design strategy when it comes to recreational public spaces. Shades from trees modify solar access at the pedestrian level and therefore, the perceived radiation by humans is lower. That was clear in the design proposal of planting trees at the above-mentioned areas (case 2

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**Figure 5.** Spatial variation of PET at 15.00 (31st August 2020) for the studied scenarios.
and 4), where Tmrt in the shaded areas can be up to 21°C (see Figure 6) lower than Tmrt of the initial unshaded state, a clear result of the reduction of the solar energy blocked by the shading structures.

The addition of trees had the largest effect on both microclimate and pedestrian comfort, as the presence of canopies of trees lowered SVF and thus the incoming solar radiation. The findings are in line with studies by [17] showing that the placement of high plants in an open schoolyard leads to a Tmrt decrease of over 22.5 °C, and indicating the improvement of PET of up to 48% by the high density of tree crown.

The spatial variation of PET was much stronger than that of air temperature, but in close relation with Tmrt. This reveals very strong dependence of PET on Tmrt that is affected by the solar access and indicates the importance of the use of thermal indices like PET, instead of individual micro-climate parameters (Ta, v), in order to quantify the human thermal conditions.

The effect of ground cover on thermal stress was also found to be important in the present study. As seen in the results, impervious surfaces like hard concrete warms-up the lower levels of the atmosphere, while water bodies that converts received solar radiation into latent heat effectively help to reduce the local air temperature.

Simulations of all investigated measures carried out, showed that shading is the most important factor that controls the thermal perception of outdoor climate. Similar conclusion on the importance of shading strategies were drawn by Nastaran [18] and Yang [19] in hot and humid climate. The addition of shading canopies, among the aesthetical amelioration, improved local thermal comfort of the courtyard.

Despite the significant effect at local scale, the ground cover and planting of vegetation have a very limited impact over the entire block for adjustment of the OTC. The absence of street vegetation will hold PET by far above the neutral range, even in case that the courtyard is occupied with high tree canopies (case 2) or fully covered with water body (case 3).

From the study results, it was obvious that environmental diversity could lead to more diversity in the outdoor thermal conditions. For cases 2, the numerous shadowed areas may be a good approach to provide preferable urban open space with high diversity of different microclimates within a small distance, and provide the users of the yard with better shelters against intense heat, supporting a healthy physical and emotional development.

5. Conclusion

The neighbourhood courtyard design has a clear impact on the local OTC, however the contemporary approach to the plan of this space at neighbourhood/ block level is likely to fail to mitigate the intense heat pollution. Different proposals for the development of pocket park were proposed in this study for the tropical city of Ha Tinh (Vietnam). The bioclimatic improvement of the yard was based mainly on adding shading canopies and reducing hard pavement. With the implementation of the redesign proposal, the average PET may be considerably reduced, but more importantly, a great amount of points...
over the yards will experience a much higher thermal comfort, facilitating a wider range of human activities and making the location more attractive.

There was a straight relation between the sun exposition (openness), Tmrt, and PET. The greater openness led to high values of Tmrt and PET, while lowering this factor by planting trees, Tmrt, and PET was consequently lowered. Strategical placement of trees in the whole area of the yard taking in mind the use of the yard is crucial. Planting trees only on the periphery of internal yard had no special effect on the thermal comfort of the whole public garden and surrounding. The choice of bare grass or sun-exposed water body for the courtyard is not a good practice, as it does not prevent solar radiation and therefore does not improve the OTC.

The courtyard configuration for the neighbourhood plan may still have a limited contribution to the improvement of OTC since cooling effect were only recognized locally where green structures were placed. Further studies on building arrangement, density and materials will be carried out to develop a comprehensive guideline on climate-responsive urban design.

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