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Optimizing Street Canyon Orientation for Rajarhat Newtown, Kolkata, India

Bhaskar DE[1]*, Mahua MUKHERJEE[2]

[1, 2] *Department of Architecture and Planning, Indian Institute of Technology, Roorkee, 247667, India*

Abstract **– Air temperature in urban street canyons is increased due to the morphed urban geometry, increased surface area, decreased long wave radiation and evapo-transpiration, different thermo-physical properties of surface materials and anthropogenic heat which results in thermal discomfort. Outdoor thermal stress can be mitigated substantially by properly orienting the canyons. It is crucial for the urban planners and designers to orient street canyons optimally considering variable local climatic context. It is important especially for cities in warm humid climatic context as these cities receive higher insolation with higher relative humidity and low level macro wind flow. This paper examines influence of canyon orientation on outdoor thermal comfort and proposes the optimum canyon orientation for the Rajarhat Newtown, Kolkata – a city in warm humid climate zone. Different scenarios are generated with different orientations. Change in air temperature, wind speed, Mean Radiant Temperature (MRT) and Physiological Equivalent Temperature (PET) of different scenarios are compared to find out the optimum orientation by parametric simulation in *ENVI_met*. Analysing the simulation results it is observed that orientation angle between 30°–60° to north performs the best for the study area of the Rajarhat Newtown. The findings of this research will be helpful for the planners to orient the street canyons optimally for future development and extension of the Rajarhat Newtown, Kolkata.**

Keywords **– Kolkata; outdoor thermal comfort; PET; street canyon orientation; urban climate; warm-humid climate**

1. INTRODUCTION

The developing world is going through the process of rapid urbanization. The urban population of developing countries has surpassed the urban population of developed nations. Being a developing nation, the economic growth and urbanization are going on at fast pace in India. As most of the future cities of India are yet to be built [1] there is scope to develop future cities with efficient, climate resilient urban design and planning strategies.

Urban outdoor spaces, often referred as ‘urban commons’, enrich the quality of urban life and are of immense importance especially in Indian context [2]. Careful design of outdoor spaces around the buildings, can reduce thermal stress of urban dwellers in densely populated cities of warm humid climate of developing world.

A large part of urban India, 18 out of India’s 53 million plus cities, falls under the warm-humid climate zone [3] including Kolkata, Chennai and Mumbai. Research on climate responsive urban design for this particular climatic zone can help to reduce outdoor thermal stress, facilitating sustainable living.

Designing street canyons is a key to climate responsive urban design as it is an intermediate interface between the urban scale and individual building scale [4], [5]. Street canyon is formed when both the sides of the street is lined by buildings. The orientation of the street canyon

* Corresponding author.
E-mail address: bhaskarde1986@gmail.com

influences solar gain and wind flow, both inside and outside of the buildings [6]. Thus, street canyon influences the cooling and ventilation of the entire urban system and subsequently affects the thermal sensation of the people and energy demand of the buildings. The study aims to optimize the street orientation to mitigate outdoor thermal stress for residential neighbourhoods of the Rajarhat Newtown – a city in warm humid climate.

1.1. Need of Study

Rajarhat Newtown is selected as the location of the study based on few practical considerations. The selection represents a city in warm humid climate region with large population base, from a developing nation. The choice is also guided by the practicality of conducting instrumented meteorological measurement considering the availability of human resource, local contacts and most importantly safety and security of the mounted portable weather stations.

The present development trend and growth pattern of the Rajarhat Newtown has met limited success in meeting the main objective of the Newtown i.e. a better living quality [7]. As the development process is still ongoing, there is future scope to integrate climate responsive urban design strategies in the course of development to achieve the envisioned goal of Newtowns, ensuring better living quality. Already built areas can also be retrofitted by corrective measures, so that the township becomes a 'Newtown' in true sense.

1.2. Literature Review

Orienting street canyons become challenging because of different needs deriving out of diverse climatological context. Number of researches attempted to provide street design guidelines befitting the climatic context depending upon the traditional and contemporary architectural wisdom [4].

A substantial amount of research is carried out on the microclimate of urban streets though these studies are concentrated on mid latitude cities. Studies for the cities in warm humid climate are quite limited [8], [9]. These studies inform that street orientation and canyon aspect ratio (the ratio of building height and the width of the canyon) are of prime importance as they take a major role in energy balance of urban canyons.

Street orientation also plays a major role modulating wind flow at street level which in turn influences human health, air quality and energy demand [6]. Table 1 summarizes the observations of notable studies on urban street orientations.

TABLE 1. RESEARCHES CARRIED OUT ON STREET ORIENTATION

Reference	Research Observations
[11]	Solar radiation and wind movement influences thermal comfort of an urban area
[12]–[14]	Orientation of urban streets is one of the important parameters that influence solar radiation and wind speed in urban areas and affects street level thermal comfort
[15]	An orientation angle between 30°–60° to the prevailing wind direction is favourable for hot humid climates of the tropics
[16]	Selection of preferable orientation is difficult as it is less predictable than solar path. Desirable orientation depends on climatic context – the need for solar access or radiation shielding, cool breeze or wind shelter
[17]	Streets canyons oriented in East-West direction, shows worst thermal condition in Fez, Morocco
[18]	Streets canyons oriented along North East-South West direction, shows worst thermal condition in Campinas, Brazil
[19]	Considering outdoor thermal comfort, North East-South West orientation is more preferable for Kolkata

1.3. Research Gap

State of the art review of literature indicates that street orientation has substantial impact on urban microclimate but general recommendations cannot be made for optimum orientation as climatic parameters and characteristics of urban fabric vary widely in the cities of warm humid climatic zone [20]. Prognostic model evaluation through analysis of meteorological parameters can adequately quantify the changes in outdoor thermal comfort due to the complex thermophysical interaction between urban climate and urban elements. This quantification of the degree of change in thermal comfort due to change in design, is crucial to optimize the orientation of urban street canyons.

Researchers have suggested context specific optimum orientation for urban areas in different climate zones based on either empirical studies or simulation based studies. Due to computational resource and time limitations, some assumptions are made to simplify urban geometry in most of the simulation based studies, considering:

– Closely spaced small buildings as a single building block [5], [21]:

This approximation does not make realistic representation of real world system and cannot predict the changes in wind flow characteristics in the spaces between the buildings. Advanced simulation tools like *ENVI_met* can model detached buildings representing real world systems;

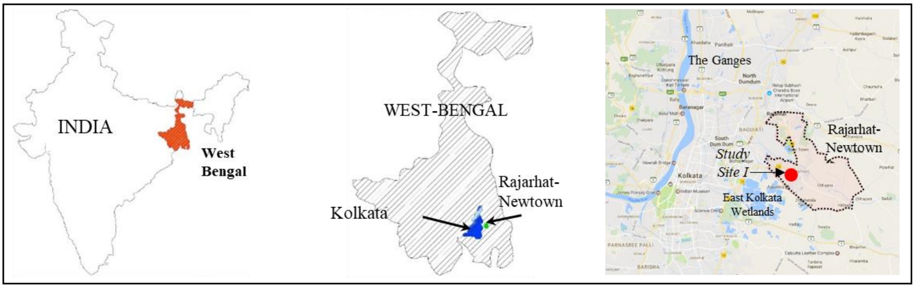
– Simulating only isolated unidirectional linear canyons [5], [17], [22]:

Laying out all the roads in a single orientation and ignoring the transverse connectivity does not happen in real world. It is important to find out optimum orientation for road layout including perpendicular roads creating a grid iron pattern common in planned urban areas and the present study area as well.

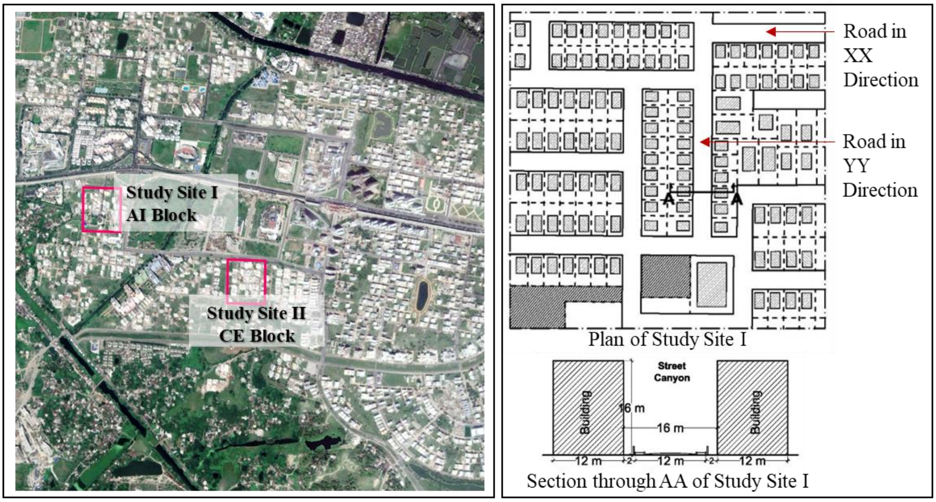
Due to the complexities discussed earlier, a general guideline cannot be proposed to find out the optimum orientation for the study area; parametric simulations are carried out. The present study is one of the first (if not the first) initiative to use numerical simulation technique for the Rajarhat Newtown, Kolkata.

This research identifies and addresses the gaps discussed above and propose a realistic solution to optimize canyon orientation for reducing thermal stress in the residential neighbourhoods of the Rajarhat Newtown, Kolkata.

2. STUDY AREA PROFILE



(a)



(b) (c)

Fig. 1. (a) Location and details of study area, (b) Satellite image of study sites, (c) Schematic plan and section of Study Site I.

The Rajarhat Newtown (22.35° N 88.28° E) of North 24 Parganas district is a growing planned city in the eastern Kolkata Metropolitan Area, 10 km away from the centre of Kolkata. It comes under tropical wet and dry climate (Aw) according to Koppen's climate classification and referred as warm humid climate zone according to the National Building Code of India, with annual maximum temperature 44 °C in April and as low as 7.2 °C in December. Average annual rainfall is 1800 mm occurring mostly in the months from June to September. Highest average relative humidity is 83 % in July–August and lowest is 58 % in February–March. Major wind flow is from south during summer and the average speed varies between 0–4 m/s [23]. Two neighbourhoods of the Rajarhat Newtown Action Area I, are selected for the present study with street canyons running in both E-W and N-S direction. The study sites are marked with dotted outlines in Fig. 1(b). Though the two study sites are studied and all the simulations are run for both the sites, the simulation results of only study site I is discussed in details in this paper.

3. ANALYTICAL FRAMEWORK

3.1. Methodology

Numerical models are versatile for their capability of dealing with several atmospheric processes and urban design variables simultaneously and considered as most reliable by some researchers [24], [25]. Method of numerical simulation is used in this study. The urban environment is modelled in the software and impacts of varying different urban parameters are assessed. Among many numerical models developed till date, *ENVI_met* [26] is used for simulation in this study for its ease of use, availability and reliability. *ENVI-met* (ver. 4.1) is a Computational Fluid Dynamics (CFD) model that simulates the interaction between built form, green cover and microclimate of urban setup in three dimensional grids. This model can simulate urban microclimatic changes and Physiological Equivalent Temperature (PET) which is instrumental in assessing outdoor thermal comfort. *ENVI_met* is tested extensively in temperate and hot dry desert climate successfully used by various researchers and also in warm humid climatic context.

Date and time duration of simulation, weather data, urban form and geometry data, material properties data, vegetation and soil characteristics data etc., are the prerequisites to carry out simulations in *ENVI_met* and are collected by site survey and through portable weather stations (*Novalynx* 110-WS-18) and thermohygrometers (refer Fig. 3(a)). A typical pre monsoon summer day (31st May) with high heat stress is selected as the simulation date and the simulation is run for 56 hours.

3.2. Scenario Generation

Seven alternate orientation options are considered to be simulated along with the existing urban setup (referred as 'base case' hereafter) to find out the optimum orientation for the study area. The study site in AI Block of the Rajarhat Newtown is oriented at angle of 5° to North. Different scenarios with their respective orientation angle are schematically represented in Fig. 2 and details are summarized in Table 1.

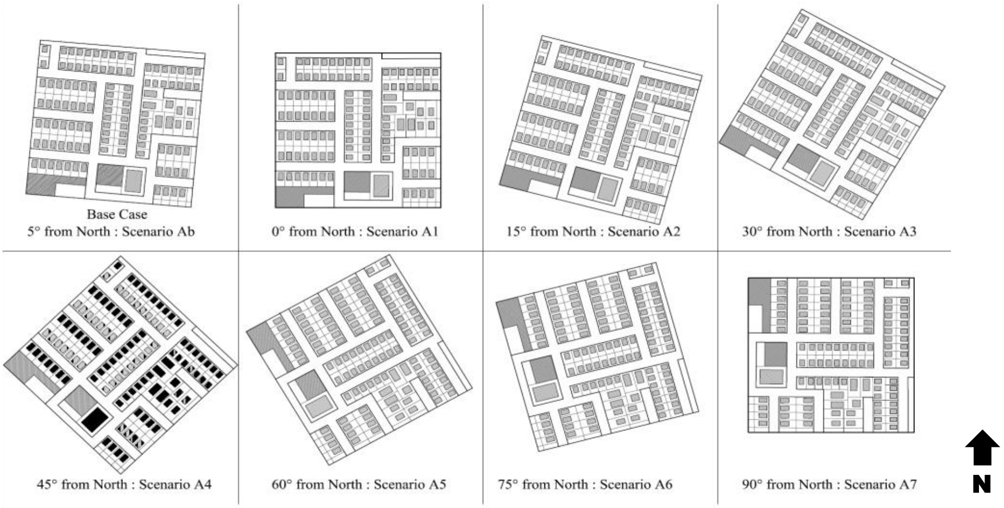


Fig. 2. Canyon orientation options.

TABLE 2. ORIENTATION SCENARIOS

Orientation	Scenario name	Remarks
Base Case	Ab	Orientation as per the base case, 5° from North
0°	A1	Orientation aligned with North, 0° angle
15°	A2	Orientation aligned at an angle 15° from North
30°	A3	Orientation aligned at an angle 30° from North
45°	A4	Orientation aligned at an angle 45° from North
60°	A5	Orientation aligned at an angle 60° from North
75°	A6	Orientation aligned at an angle 75° from North
90°	A7	Orientation aligned at an angle 90° from North

4. VALIDATION

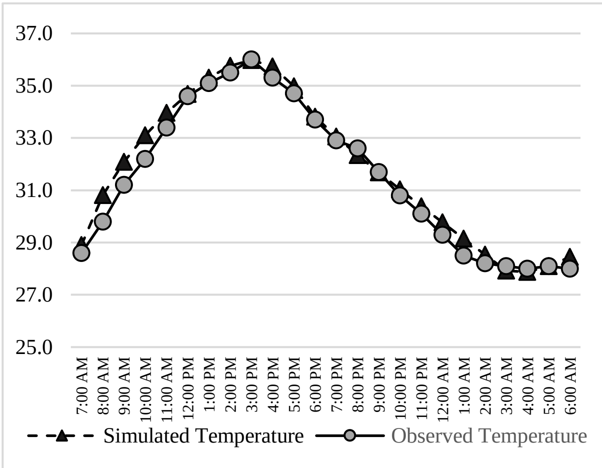
Computer simulation models are developed for creating credible representations of actual real world systems. As computer simulation models never exactly represent the real world systems, validation is necessary to determine the degree of accuracy to which a simulation model and its associated data are replicating the real world from the perspective of the intended uses of the model [27]. Air temperature profile generated by simulation is compared with real world data (collected by survey) for the same time period for validating the model created in *ENVI_met*.

A methodology suggested by Willmott [28], [29] is followed to check accuracy of the validation model by calculating the Root Mean Square Error (*RMSE*) and Index of Agreement (*d*). The RMSE value helps to determine the model performance by measuring difference between the simulated (*S*) and the observed (*O*) air temperature. Index of Agreement (*d*) is a descriptive measure for model evaluation which can indicate to which extent the simulated values are error free [28]. It can have a value ranging from 0.0 to 1.0 where the value 1.0 means absolute agreement indicating the fact the simulated values (*S*) are equal to the observed values (*O*).

(a)

R^2 value	0.972
RMSE	0.411 °C
Index of Agreement	0.995

(b)



(c)

Fig. 3. (a) Instruments used, (b) Validation data, (c) Validation graph.

The observed and simulated maximum temperature is 36 °C and 35.9 °C respectively around 2 pm and minimum temperature is 26.4 °C and 26.3 °C respectively around 3 am. Simulated temperature profile (*S*) exhibits good coherence with the temperature profile obtained by real world on site measurement (*O*) till 7 am. The model starts to overestimates the air temperature slightly after 7 am which disappears at 12 noon. The difference is caused by sea breeze due to the adjacency of the study site to the Bay of Bengal (around 70 km). Simulated temperature again shows good coherence from 12 noon to 8 pm as the effect of the sea breeze goes away. After 9 pm, simulated air temperature starts to show a tendency to overestimate which peaks around 1 am by 0.7 °C. The difference gradually decreases and the simulated temperature and observed temperature becomes almost equal around 3 am (refer Fig. 3(c)). Similar overestimation of nocturnal temperature is observed by other researchers [30]–[32]. The probable reason is inadequate computation of heat storage in building mass by the model for keeping the indoor temperature of the buildings constant throughout the whole simulation [31].

Simulated temperature showed coherence to the observed temperature with an R^2 value of 0.972, *RMSE* of 0.411 °C (which is 1.55 % of minimum temperature of the day), and an index of agreement (*d*) of 0.995 (see Fig. 3(b)). It is observed that the model represents the thermal environment with an acceptable degree of accuracy considering the validation range referred by researchers [31].

5. RESULTS AND DISCUSSION

Generated scenarios are simulated and three meteorological parameters: air temperature, wind speed and Mean Radiant Temperature (MRT) are compared for 24 hours on 31st May. Outdoor thermal comfort for all the scenarios including the base case is assessed by comparing Physiological Equivalent Temperature (PET). PET is a thermal comfort index extensively used for outdoor thermal comfort studies and widely acceptable for warm humid climate. The comparative study of simulation results for different scenarios helps to identify optimum orientation to reduce outdoor thermal stress in a typical residential neighbourhood of the Rajarhat Newtown. The simulations are carried out for 0°–90° with 15° increment. The results of scenario A5, A6 and A7 (orientation angle 60°, 75° and 90°) are closely similar to results of their counterpart i.e. scenario A3, A2 and A1 (orientation angle 30°, 15° and 0°) respectively, though not identical; i.e. an orientation angle between 45°–60° performs similarly as the orientation angle between 30°–45° and so on. Additionally, scenario A1 (0°) and scenario Ab (5°) also performs almost identically. So, only the scenario Ab, A2, A3 and A4 are compared (refer Fig. 4).

5.1. *Air Temperature*

The simulated maximum air temperature at 2 pm is reduced to 42.4 °C from 42.7 °C compared to the base case when the site is at an angle of 15° from north (scenario A2). For scenario A3, the maximum temperature reduced to 42 °C which is 0.7 °C lower than the base case Ab. In scenario A4, the maximum temperature (42.3 °C) increases slightly (0.3 °C) compared to the previous scenario (A3) (refer Fig. 4; 1st row). An overall air temperature reduction can be observed in the densely built parts of the study area if aligned obliquely. Minor temperature increase can be found in the areas around the green open spaces.

5.2. *Wind Speed*

The change in orientation also influences the wind speed and wind flow pattern. It increases wind speed in the roads laid along XX direction but reduction is observed on roads along YY direction (refer Fig. 1(c) for XX and YY direction roads). In scenario A2, the reduction of wind speed along YY roads is in between 0.1–0.3 m/s whereas the speed increase in XX roads is 0.3–0.7 m/s. The improvement in wind movement pattern and speed becomes more prominent in scenario A3 compared to the previous scenario (A2). Maximum wind speed increases and reaches at 2.96 m/s showing a substantial improvement of wind speed along the roads in XX direction (up to 1.3 m/s). Wind speed in the roads both in XX and YY direction are almost similar in this case where in scenario Ab, the roads in XX direction were almost devoid of perceptible wind flow. The difference in wind speed between two sides of the buildings aligned along the road improves the cross ventilation within the buildings and improves the ventilation potential in spaces between two adjacent buildings. The reorientation increases wind speed of the roads in XX direction compared to the previous scenario A2. Scenario A4 creates a more uniform wind field with a negligible improvement of 0.1 m/s compared to previous scenario A3 (refer Fig. 4; 2nd row).

5.3. Mean Radiant Temperature

In scenario A2, a narrow space on the southern sidewalk of the XX direction roads (representing MRT of 51.0–54.3 °C), is created by the shadows cast by the buildings. In scenario A3, the narrow shaded zone with lower MRT by the edge of the buildings along the roads in XX direction is widened and a continuous space of 2–4 m width with MRT 47.7–51 °C is created along the side of the roads in YY direction, which was non-continuous in both the previous scenarios (Ab and A2). The continuous band of low MRT at one side of both types of roads (in XX and YY direction) is advantageous for pedestrian comfort. An overall reduction of MRT by 1–3 °C is also observed in most part of the area compared to the base case Ab. In scenario A4, MRT remains similar as scenario A3 in the majority of the area though it increases in the space between buildings. The band of continuous shaded space with comparatively lesser MRT remains on one side of both roads along XX and YY direction (refer Fig. 4; 3rd row).

5.4. Physiological Equivalent Temperature

Change in PET is observed in different scenarios due to the change in the environmental variables like air temperature, wind speed and MRT. The pattern created by bands with lesser MRT is present in all generated scenarios (A2, A3 and A4), representing a significant improvement in thermal comfort on streets compared to Base Case (Ab) especially in roads of XX direction. In scenario A2, PET on roads in XX direction is reduced (1.5–2.5 °C on average) as the wind movement on those streets have improved. But there is no significant change in PET on the streets parallel to the wind direction (YY direction). Reduction of PET can also be noticed in the spaces between the buildings. In scenario A3, the overall reduction of PET is more prominent (average reduction of 3–4 °C) compared to the previous scenarios Ab and A2. The scenario A4 does not exhibit any further improvement in comfort level compared to the previous scenario A3. Rather a mild deterioration in comfort level can be observed though reduction of thermal stress can be observed if compared to Base Case Scenario (Ab) and scenario A2.

The scenarios A5 (60°), A6 (75°) and A7 (90°) are not discussed here in details due to space limitation and avoid repetition as their results are almost identical to the scenario A3, A2 and A1 respectively. The climatic variables remained same but the direction of the shadow cast by the buildings is changed for these scenarios due to mirrored orientation of scenario A3, A2 and A1.

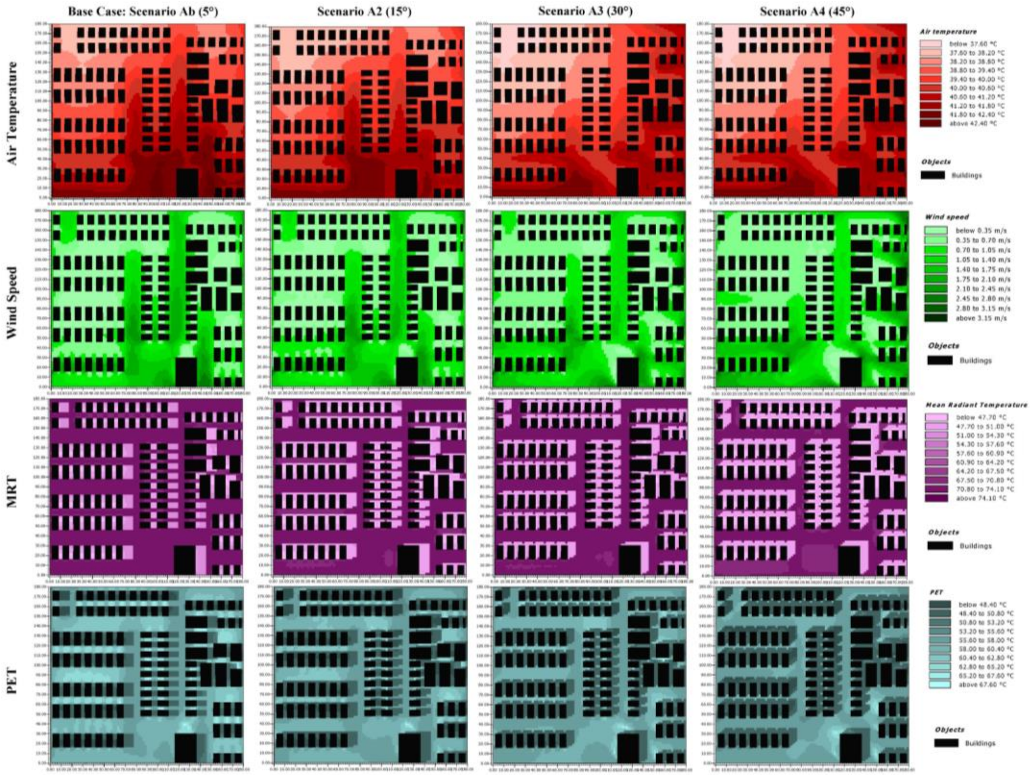


Fig. 4. Air temperature, wind speed, MRT and PET of scenario Ab, A2, A3 and A4.

5.5. Discussion

The analysis of simulated scenarios exhibit perceptible change in the air temperature, wind speed and MRT due to different orientations and as a result thermal comfort is affected (which is quantified by comparison of PET).

Maximum reduction in air temperature is recorded in the scenario A3. The scenario also shows substantial improvement in wind speed and reduction in average MRT due to increased shading of streets by the buildings. This improvement in outdoor thermal comfort is confirmed by the PET map as well. The shaded zone created on streets provide less stressful outdoor thermal environment. The comparison of PET values brings out scenario A3 as the best performing one but scenario A4 performs almost similarly. The counterpart of scenario A3, i.e. scenario A5 (60° to North) too performs similarly as scenario A3.

The reduction in thermal stress level can be observed throughout the temporal range, but the thermal stress reduction is much more pronounced in the mid and late afternoon (after 2 pm) (refer Fig. 5). At 4 pm, PET is reduced by 1 °C in 10 % area, by 2 °C in 19 % area, by 3° in 18 % area and up to 10 °C in around 16 % area. Slight increase in temperature up to 3 °C can also be observed in 5 % area. PET of rest of the area cannot be calculated as it is covered by the buildings (refer Fig. 5; 4th row, 4th column).

If the street canyon is oblique to prevailing wind direction, difference in wind speed is observed between two adjacent sides of the building which subsequently creates pressure difference. As one of the sides of the buildings fall under pressure zone and the other in suction zone, the potential of cross ventilation is enhanced. The benefit of natural ventilation of the buildings due to pressure difference is maximum at the outward limit of 30° to 60° range. It is maximum at the boundaries (30° and 60°) and is reduced towards the centre i.e. at 45°. This benefit of improvement in passive ventilation can be observed due to more realistic representation of the study area by modelling individual buildings instead of considering the buildings as a single continuous block.

It is observed if pedestrian level wind flow and outdoor thermal comfort is considered, any orientation angle between 30° to 60° performs similarly for a site where the wind flows from the southern direction during summer. But orientation close to 30° or 60° to north has the additional potential for improved natural ventilation of the buildings and better pollutant dispersal.

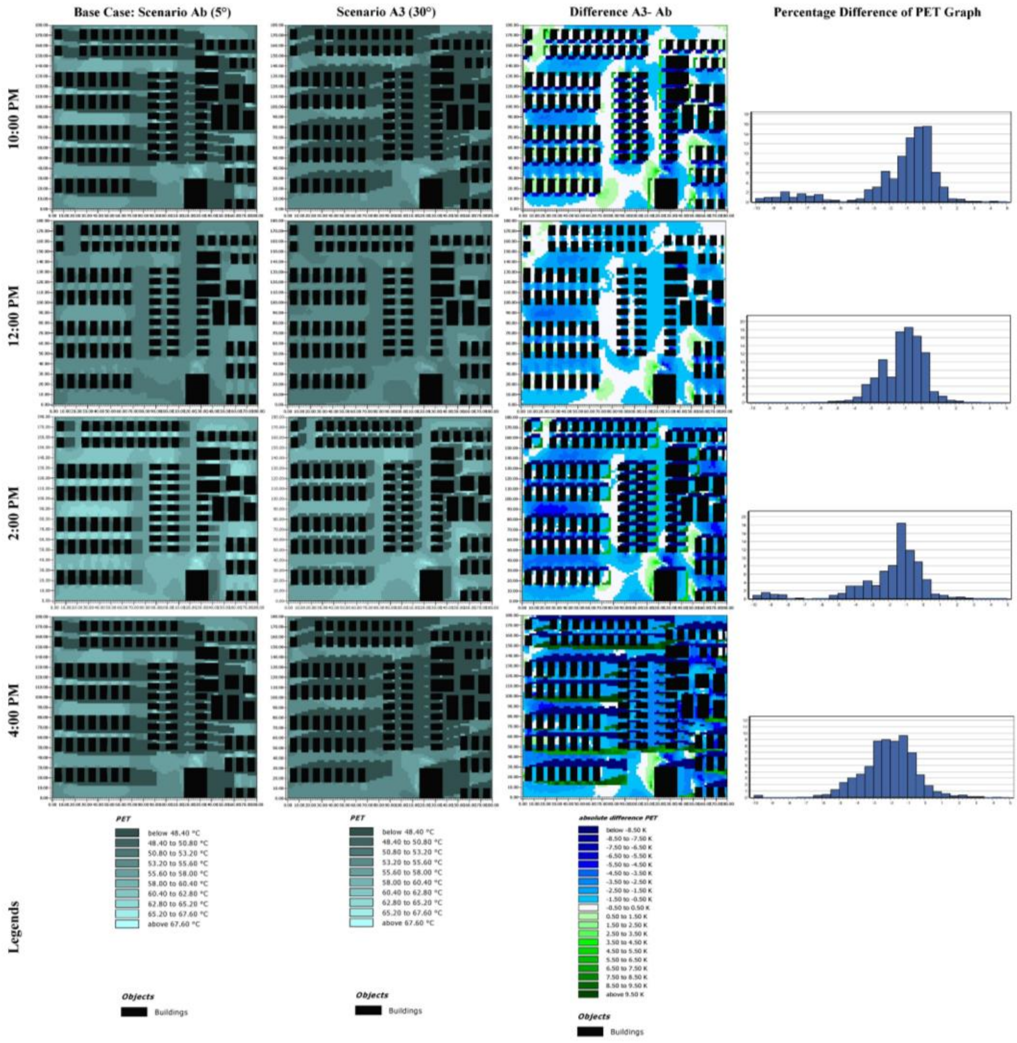


Fig. 5. Temporal variation of PET.

6. Conclusion

Results of the parametric study reveals that orientation angle of 30° to 60° from North (scenario A3, A4 and A5), performs more efficiently to reduce the outdoor thermal stress in the Rajarhat Newtown. Improvement of thermal comfort and ventilation of the buildings was proposed by Givoni [33] for warm humid climate by orienting them an angle between 30° to 60° with the prevailing wind direction. Kruger et al. [34] also has reported that similar orientation facilitates better wind movement around the building. The present research reaffirms the previous findings for the Rajarhat Newtown case.

The above-mentioned orientation angle for the study area can reduce ambient air temperature, create better wind movement and shading resulting in improvement of outdoor thermal comfort on the streets and better pollutant dispersal [35] which are desirable in warm humid climate. Reduction in ambient air temperature and improvement of ventilation can also reduce energy demand and peak load [9], [36]. The improvement in thermal environment is more pronounced during the afternoon when the heat stress is extreme. The findings of this research will assist the planners to orient the street canyons optimally for future development and extension of the Rajarhat Newtown, Kolkata.

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Bhaskar De obtained his Masters of Architecture degree in 2012 from Indian Institute of Technology, Roorkee and completed his Bachelor of Architecture in 2010 from Indian Institute of Engineering, Science and Technology, Shibpur (formerly known as Bengal Engineering and Science University) with First Class. Presently, he is a doctoral candidate in the Department of Architecture and Planning, IIT Roorkee, India, since 2013.
After completion of Master's Degree, he served as a Lecturer in National Institute of Technology, Hamirpur, India, for one year. His research interest lies in the fields of urban climate study, urban design, thermal comfort, building energy studies and energy efficient retrofitting. He is awarded fellowships from the Ministry of Human Resource Development, Government of India, from 2010 to 2012 and from 2013 to present. He presented his work in 4th IC2UHI- 2016 conference, held in Singapore and received the student award. Contact details: Department of Architecture and Planning, Indian Institute of Technology, Roorkee, Uttranchal, India, PIN–247667.
E-mail: bhaskarde1986@gmail.com, bhasddap@iitr.ac.in; Tel.: +91 9410165684.

Dr. Mahua Mukherjee did her graduation in Architecture and post-graduation in Building Science and Technology. Her doctoral study resulted in developing the Sustainable Total Living Environment (SusTLE) model. She teaches in the Department of Architecture and Planning, IIT Roorkee, India since 2003. As Fulbright Fellow she conducted post-doctoral research on urban resiliency in the Pennsylvania State University in 2008. As Visiting Research Faculty, she spent 3 months with DPRI, Kyoto University to work on green resilient infrastructure.

She has completed research project on Surface Transformation due to Urban Dynamics in institutional campuses and its environmental impact; and ongoing projects are: 'Translating Urban Spaces as strategic Energy and Water security measure', and 'Evaluation of the Monolithic Construction with Structural Stay in place CR steel specially designed formwork system Housing Technology w.r.t. Green and Sustainability Parameters'. Some of the notable research publications of Dr. Mukherjee are: i) Memari A., Mukherjee M., Solnosky R. Comparative Study of Various Wall Systems' Performance Attributes in Different Environmental Conditions. *International Journal of Architecture, Engineering and Construction* 2015:4(2):64–79; ii) Pawar A. S, Mukherjee M., Shankar. R. Thermal Comfort Design Zone Delineation for India Using GIS. *Building and Environment* 2015:87:193–206; iii) Mukherjee M. Eco-Environmental Factors in Green Roof Application in Indian Cities. *Journal of The Institute of Engineers (India): Series A* 2014:95(3):137–142.

Contact details: Department of Architecture and Planning, Indian Institute of Technology, Roorkee, Uttranchal, India, PIN–247667. E-mail: mahuafap@iitr.ac.in; Tel.: +91 9411500150.