An Evaluation of Increasing Building Height in Respect of Thermal Climate in a High Density City in South Asia Using Numerical Modeling

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Abstract

In this paper, the influence of building height on the thermal climate in urban canyons is discussed. The investigation was carried out using a three-dimensional numerical model with high spatial and temporal resolution that simulated the microclimatic changes in urban environments. Model calculations were performed for a typical summer day in Dhaka, Bangladesh, a city in South Asia with a high population density and tropical climate. Two existing urban canyons in the city center with different height to width ratios, and projected canyons with increased building heights were investigated for daytime conditions. The thermal climate was evaluated on the basis of solar radiation, air temperature $T_a$, and mean radiant temperature $T_{mrt}$, mostly along the pedestrian ways. The results show that with respect to daytime thermal climate depending on $T_a$, greater building height was more advantageous in the case of shallow canyons than for deeper canyons. However, the mean radiant temperature $T_{mrt}$ on the pedestrian ways was found to be 30 –40°C higher than $T_a$ for sunny conditions; however, for shaded conditions, the difference was minimal. Finally, considerable decreases in $T_{mrt}$ were found in projected canyons compared with existing canyons, especially during those times of the day when there is shade.

Keywords: urban canyon; sky view factor; mean radiant temperature; thermal climate

1. Introduction

Many cities in South Asia are currently undergoing rapid urbanization. This is causing changes in land use, urban form, and ground cover. Incorporation of climate issues in urban planning and design is of increasing importance. However, the planning and design issues related to climate are not properly considered in South Asia. The important urban design elements that affect the urban microclimate are the size of the city, orientation and width of streets, density of the built-up area, height of the buildings, and the presence of parks and other green areas ¹. Therefore, it is possible to modify the urban climate through the physical restructuring of a city and appropriate urban policies. The height of buildings is an independent design feature that can affect urban density as well as the urban climate in many ways. Studies in Pune, India, showed that the unplanned increase in heights of buildings increases the discomfort level in a city ². However, in the case of Colombo, Sri Lanka, it was found that the wide streets with low-rise buildings and no shade trees made the outdoor conditions worse, and the most comfortable conditions were found in narrow streets with tall buildings, especially if shade trees were present ³. In addition, it was found that a very deep street canyon had considerably lower air temperature than a shallow street canyon ⁴. These studies were conducted for existing canyons.

There are only a few studies on the urban outdoor thermal environment in tropical climates. Most of the previous studies extend indoor comfort evaluation methods to the outdoors by considering only air temperature, humidity, and wind speed ⁵-⁶. In these studies, the mean radiant temperature, $T_{mrt}$ is assumed to be equal to the air temperature, $T_a$. However, this assumption cannot accurately reflect the outdoor reality. In fact, $T_{mrt}$ is the key variable in evaluating thermal sensation outdoors during the daylight hours in summer, since it has been confirmed that human comfort indexes such as predicted mean vote (PMV) and physiologically equivalent temperature (PET) are strongly dependent on $T_{mrt}$ ⁷.

This research is based on conditions in Dhaka, Bangladesh, a location in South Asia within the tropical monsoon climate zone. Presently, in Dhaka city, increasing the heights of buildings is commonly adopted to cope with the rapid urbanization. Moreover,
heat stress in summer is a growing environmental concern for Dhaka city. Thus, there is an urgent need to evaluate the effects of building heights on the thermal climate in the city. In this study, the thermal climate is evaluated by taking into account the solar radiation, air temperature, and mean radiant temperature.

2. Study Area

Dhaka city is a fast growing mega city. It is located at 23.24°N, 90.23°E, and 8.8 m above sea level (asl). Approximately 12.3 million people live in the metropolitan area, resulting in a high density of about 43,797 persons per square kilometer. To accommodate this large population, the city is growing both horizontally and vertically. This study is based on a locality in the center of the city of Dhaka—the Motijheel Commercial Area—located in the southern part of the city. The average height of buildings, \( H \) in this area is about seven stories; the height of a single-storied building is 3 m. Two urban canyons with different widths, \( W = 42 \) m and 18 m for Canyon 1 and Canyon 2, respectively) were selected for this study, as shown in Fig.1. Both canyons are located in an area surrounded by 1- to 10-storied commercial buildings, and the busiest roads in terms of traffic and pedestrian ways. Buildings higher than 10 stories were built before the present rules regarding building height were developed. The orientations of Canyon 1 and Canyon 2 with the NW-SE direction are about 32° and 10°, respectively.

This study was carried out for hot and dry summer conditions (March-May). During this season, the solar radiation on a horizontal surface is high compared to the rest of the year, and the maximum occurs in April (5.00 kWh/m²). The probabilistic extreme predicts the maximum temperatures in April to be as high as 39.1°C (1 in 4 years), 40.2°C (1 in 10 years), and 41.0°C (1 in 25 years). The relative humidity in this period is about 70%, and the near-ground wind speed is about 2.5 m/s, with slight variation during the daytime.

3. Increasing Building Height: Projected Canyons

At present, the growth and development of Dhaka city is regulated by the Dhaka Metropolitan Development Plan (DMDP) 1995–2015. One of the major features of the preferred strategies of this plan is: an acknowledgement of continuing densification throughout the whole planned period in both older established urban areas and in those areas developed since the early 1980’s. As a result, the previous rule regarding height limitation has been relaxed allowing higher buildings in some parts of the city. In this study, the existing buildings lower than 10 stories are extended by a maximum of 4 stories to attain heights of 10 stories in both the canyons. This limited increase of building height is considered here because the building coverage, set back, and other guidelines are different for buildings higher than 10 stories. Moreover, if all buildings are of the same height, wind speed and natural ventilation at street level are decreased. The ground coverage, design, and materials of the buildings are considered to be unchanged. The layouts of existing canyons with building heights in stories and proposed heights in projected canyons (in parentheses) are shown in Fig.2. After increasing the building height, the average aspect ratio \( H/W \) is increased from 0.4 to 0.6 for Canyon 1 and from 1.1 to 1.5 for Canyon 2. Fig.3. shows the sky view factors (SVF) at a height of 1.2 m above ground for the existing and projected canyons.

4. Methodology

4.1 Numerical Modeling

In urban climatology, an extremely limited number of field studies related to outdoor thermal comfort and its dependence on urban growth are available due to the large number of urban variables and processes involved. Thus numerical modeling is more popular.

Fig.1. Study Area in the Motijheel Commercial Area, Dhaka

Fig.3. Sky View Factors of (a) Existing Canyon 1, (b) Projected Canyon 1, (c) Existing Canyon 2 and (d) Projected Canyon 2
than comprehensive field measurements, because researchers have greater control over modeling, and it is more economical with regard to time and resources. The governing equations for the simulation of present urban microclimate are based on the fundamental laws of fluid dynamics and thermodynamics, consisting of unsteady 3-D incompressible Navier-Stokes equations. To account for the turbulence inside the canyon, a 1.5 order turbulence model is coupled. These equations are too numerous to be presented here but can be found in\(^\text{11,12}\). These non-linear partial differential equations are solved on a staggered grid system using the finite difference method.

**Mean Radiant Temperature** \(T_{\text{mrt}}\)

Human comfort from indoors to outdoors can be assessed by mean radiant temperature \(T_{\text{mrt}}\). This parameter sums up all short-wave and long-wave radiation fluxes that are absorbed by a human body and affect its energy balance. \(T_{\text{mrt}}\) at street level for each grid point on the \(z\) axis (the vertical direction) can be expressed as\(^\text{13}\):

\[
T_{\text{mrt}} = \left[ \frac{1}{\sigma} \left( E_{t}(z) + \alpha_{m} \epsilon_{p} (D_{t}(z) + I_{t}(z)) \right) \right]^{0.25}
\]

All radiation fluxes such as direct irradiance \(I_{t}(z)\), diffuse and diffusively reflected solar radiation \(D_{t}(z)\), and total long-wave radiation flux \(E_{t}(z)\) from the atmosphere, ground, and walls, are taken into account. In this equation, \(\sigma\) is the Stefan-Boltzmann constant \((5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4)\), \(\alpha_{m}\) is the absorption coefficient of the irradiated body surface for short-wave radiation \((=0.7)\), and \(\epsilon_{p}\) is the emissivity of the human body \((=0.97)\). At street level, 50% of \(E_{t}(z)\) is assumed to originate from the upper hemisphere (sky and buildings) and 50% from the ground \((E_{g})\), and it is expressed as:

\[
E_{t}(z) = 0.5 \left[ (1 - SVF(z))E_{w} + SVF(z)E_{g} \right] + 0.5\epsilon_{p}E_{g}
\]

The sky view factor \(SVF(z)\) is given by:

\[
SVF(z) = \frac{1}{360} \sum_{\pi=0}^{360} \cos\lambda(\pi)
\]

Here, \(\lambda\) is the vertical angle determined by an obstacle at the azimuth angle \(\pi\). \(E_{g}\) is the downward radiation flux from the visible part of the sky weighted by SVF. Radiation emitted by the walls, \(E_{w}\) and heat fluxes from the ground, \(E_{g}'\), are calculated by the Stefan–Boltzmann law.

Total diffuse radiation \(D_{t}(z)\), which comes partly from the sky \((D_{s})\) and partly from the walls as diffusively reflected solar radiation \((\alpha_{m}I_{t})\), is expressed as:

\[
D_{t}(z) = \left[ 1 - SVF(z) \right] \alpha_{m} I_{t}(z) + SVF(z)D_{s}
\]

where \(\alpha_{m}\) is the mean albedo of the model area.

The human body absorbs only a part \((I_{t}(z))\) of the direct solar irradiance \((I_{s}(z))\). This is expressed by an empirical formula of the surface projection factor \(f_{p}\) of a standing person:\(^\text{13}\):

\[
I_{t}(z) = f_{p} I_{s}(z)
\]

The above mentioned equations were solved on the ENVI-met simulation environment\(^\text{15}\). This model calculates all important meteorological parameters such as air and surface temperatures, wind speed, humidity, radiation, and mean radiant temperature. The versatility and validity of ENVI-met were confirmed in the previous studies\(^\text{16,17}\). For temporal stability of the numerical simulation, the time step was kept below 10 s. The basic input parameters for simulation are given in Table 1.

**5. Results and Discussion**

Fig. 4. shows the measured (by Meteorological Department, Dhaka\(^\text{18}\)) and simulated air temperatures \(T_{a}\) in the month of April for the existing case for Canyon 1. Though some differences exist between measurement and simulation, it is found that ENVI-met can predict diurnal temperatures accurately. Furthermore, a strong correlation \((R^2 = 0.79)\) exists between these two sets of values. Thus the validity of ENVI-met simulation is confirmed in the present research.

The thermal climate at the central points of the pedestrian ways (points A and B) as well as along the pedestrian ways (Line 1 and Line 2) shown in Fig.2., will be discussed in the following sections. Pedestrian ways are 3 m away from the respective sides of the buildings. Parameters are evaluated at a height of 1.2 m above ground as this height is representative for the comfort assessment for a standing person.

**Solar radiation**

The direct \(S\) and diffuse \(D\) components of the hourly mean short-wave radiation at the pedestrian way in Canyons 1 and 2 are presented in Figs.5. and 6.,
is found along the two sides of the pedestrian way to the reduced Dhaka), which in this month is highest at this time. In the because of the effect of the position of the sun (75.9° for W/m² increases with increasing building height. However, D does not exceed 107 W/m² and reaches this maximum value at 12:00 LST in all cases.

In the case of Canyon 1 (Fig.5.), on adding the S and D components, it can be observed that on both sides of the pedestrian way, G is highest (>1000 W/m²) from 10:00 to 14:00 LST. It reaches its highest value of 1065 W/m² in the existing canyon at point A at 12:00 LST because of the effect of the position of the sun (75.9° for Dhaka), which in this month is highest in this time. In the projected Canyon 1 at points A and B, G decreases due to the reduced S component although the D component increases slightly.

In Canyon 2, a reverse effect because of shadows is found along the two sides of the pedestrian way respectively. Since the global radiation (G) is the sum of S and D, the value of G is mostly affected by the direct solar radiation S because of the tropical location and clear sky conditions. S decreases as the sky view factor decreases and also as the H/W ratio increases in the projected canyons. Inversely, after increasing building heights, D rises in both canyons. This is due to the increase in diffusely reflected radiation with increasing building height. However, D does not exceed 107 W/m² and reaches this maximum value at 12:00 LST in all cases.

In the case of Canyon 1 (Fig.5.), on adding the S and D components, it can be observed that on both sides of the pedestrian way, G is highest (>1000 W/m²) from 10:00 to 14:00 LST. It reaches its highest value of 1065 W/m² in the existing canyon at point A at 12:00 LST because of the effect of the position of the sun (75.9° for Dhaka), which in this month is highest in this time. In the projected Canyon 1 at points A and B, G decreases due to the reduced S component although the D component increases slightly.

In Canyon 2, a reverse effect because of shadows is found along the two sides of the pedestrian way at points A and B, which is shown in Fig.6. In this case the point A is mostly unfavorable with respect to radiation because the duration of solar exposure is the highest (9 h). Whereas point B is in the favorable position because there is no S component of radiation after 10:00 LST. However, on both the points of projected Canyon 2, G decreases to some extent.

Air temperature

Fig.7. Contour Maps of Air Temperature T_a inside Canyon 1; (a) Existing and (b) Projected at Time-12.00 LST

Fig.8. Contour Maps of Air Temperature T_a inside Canyon 2; (a) Existing and (b) Projected at Time-12.00 LST

Figs. 7. and 8. show the contour maps of air temperature T_a at 12:00 LST inside the existing and projected Canyons 1 and 2, respectively. At this time of the day, the effect of extended shading is not clearly noticeable. However, the reduction of T_a from the existing to the projected canyon is quite obvious, as shown in these figures. The air temperature T_a in the existing Canyon 1 varies from 32.4°C to 34.0°C, while
for the projected canyon, $T_a$ varies in the range of 31.5° to 33.3°C. From Fig.8., it can be seen that $T_a$ ranges from 31.8° to 32.9°C and 31.4° to 32.3°C for existing and projected Canyon 2, respectively, at this hour of the day.

The diurnal evolution of $T_a$ is shown in Figs.9. and 10. at the points A and B on the pedestrian ways along the two sides for the canyons. For all cases in the projected canyons, $T_a$ decreases with the decline of SVF. However, the decreasing rate of $T_a$ is different. Fig.9. shows that in the shallow canyon (Canyon 1) after increasing building height, $T_a$ decreases considerably from 9:00 LST to 16:00 LST at point A, and the maximum decrease is found to be 0.87°C at 10:00 LST. However, at point B, there is a significant decrease in $T_a$ in the afternoon hours and the maximum (1.1°C) occurs at 16:00 LST. The shadow effect of the buildings is just the reverse with respect to time on the two sides of the pedestrian way, and thus, this affects the difference in $T_a$ between points A and B. However, the average decreases in temperature at points A and B are 0.62°C and 0.60°C, respectively.

In Canyon 2, on both the sides of the pedestrian way, $T_a$ decreases in the projected canyon almost uniformly throughout the day, as shown in Fig.10. Because Canyon 2 is similar to an E-W oriented canyon with an inclination of 10° towards the NW-SE orientation, there is longer exposure of solar radiation in this canyon. Thus, from noon and into the afternoon, with the increase in $T_a$, the difference in $T_a$ between the two sides of the pedestrian way also increases. The average decreases in temperature at points A and B are 0.49°C and 0.42°C, respectively.

**Mean Radiant Temperature**

Figs.11. and 12. show the distribution of mean radiant temperature $T_{mrt}$ inside Canyons 1 and 2, respectively, at 10:00, 12:00, and 14:00 LST. Its variation pattern at different hours of the day is totally different, unlike that of $T_a$. It can be observed that although the maximum global radiation in all the canyons occurs at 12:00 LST, this is not the case for $T_{mrt}$. Indeed, $T_{mrt}$ is always related to the radiation fluxes received by a standing human, but it is not an absolute measure of the surrounding surface temperatures. At 12:00 LST in Dhaka, the sun is at its highest position, and high radiation values are found for horizontal surfaces; however, the projected surface area where solar radiation is incident on the human...
body is relatively small for a standing person (only the head area and parts of the shoulders). Conversely, when the sun is lower on the horizon, radiation may not be higher than that at noon, but it is incident on a much larger surface of the human body and causes $T_{mrt}$ to increase. These situations are illustrated in Figs. 11. and 12.

Fig. 11. shows that in the case of Canyon 1, $T_{mrt}$ decreases almost uniformly by 3°C in the projected canyon between 12:00 and 14:00 LST. It also shows that at 10:00 LST, the difference in $T_{mrt}$ is very large, about 40°C along Line 1, on most of the pedestrian way, due to shading. On the other hand, on some parts of the pedestrian way, in front of the tallest unchanged buildings, $T_{mrt}$ values for existing and projected canyons are quite similar. Moreover, Fig. 11. (b) illustrates that at 14:00 LST, because of the shading effect, $T_{mrt}$ declines considerably (about 37°C) on some additional parts of the pedestrian way, due to the maximum extension in building height.

In the case of Canyon 2 and along Line 1 (Fig. 12. (a)), it is obvious that $T_{mrt}$ is very high. In the existing canyon, $T_{mrt}$ reaches maximums of 75°C, 70°C, and 77°C at 10:00, 12:00, and 14:00 LST, respectively. In the projected canyon, it shows a variable decrease of up to 3°C on most of the parts of the pedestrian way. There is no shading effect on this side of the pedestrian way during these hours of the day and so $T_{mrt}$ increases. Again on the other side of the pedestrian way (Line 2), the shading continues from 10:00 LST until the rest of the day, and as a result, $T_{mrt}$ is lower in this case, as shown in Fig. 12. (b). $T_{mrt}$ decreases to some extent in the projected canyon, by 3°C on average, at 10:00 and 12:00 LST. Moreover, at 12:00 LST, $T_{mrt}$ falls abruptly in both the existing and projected canyons in front of the tallest buildings, due to shading effects. At 14:00 LST, $T_{mrt}$ falls significantly (35°C) on some parts of the pedestrian way in the projected canyon, due to the shading effect.

Comparing Canyons 1 and 2, it can be observed that Line 1 of Canyon 2 is the most uncomfortable with respect to $T_{mrt}$. In the case of Line 2, both the canyons show similar patterns of $T_{mrt}$ at 10:00 and 12:00 LST. On the other hand, at 14:00 LST, $T_{mrt}$ decreases considerably on some sections of the pedestrian way.

6. Conclusions
The important findings of the present study are that
- The increased building height causes the mean radiant temperature to decrease to about a maximum of 40°C, due to the shading effect, at certain hours of the day. On the unshaded parts, $T_{mrt}$ decreases about 3°C at other hours of the day.

This study has demonstrated that the policy of increasing building heights to some extent can offer a better thermal climate in the case of a high-density city in South Asia where coping with urbanization is a challenging issue. Further, the results obtained from this research can contribute to the urban design process to achieve a more comfortable urban environment by mitigating heat stress in the summer.

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