Numerical simulation on the outdoor thermal comfort in view of urban renewal: A case study of Changsha, China

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Abstract. Urban Renewal plays an important role in urban economic development and urban construction in China. A large number of cities are currently developing towards high-rise and high-density models which will affect microclimate. Firstly, it analysed the impact on urban wind and thermal environment during the removal and reconstruction of residential buildings using ENVI-met. Secondly, the correlation between wind and the thermal environment with building arrangement, building density, building height and green ratio in 7 ideal cases were studied. Thirdly, the Physiologically Equivalent Temperature (PET) index was simulated by RayMan to assess thermal sensation. Finally, a case study of Changsha was simulated, where a factory was reconstructed to residential buildings. The results showed that 1) The redeveloped site will affect the neighbour outdoor thermal comfort within the range of 100m, and the impact will be insignificant beyond 100m. 2) During the daytime, higher building height and building density can result in 0.05°C-0.13°C lower PET value. 3) Green space is more effective than the residential area in cooling at night during the summer.

1. Introduction
Urban Renewal, which has been discussed since the 1970s in China, is mainly characterized by the “demolish-and-reconstruction” of the city’s declining land, replacing by a more comfortable living environment. It plays an important role in urban economic development and urban construction in China [1]. During the period 1979–1987, driven by housing system reform, the government and the state-owned enterprises were responsible for the construction of employees’ housing, most of which were high-density, low-rise building blocks with low green ratio setting in a linear layout. However, the welfare housing system was completely abolished during the market acceleration period. A large number of buildings were gradually demolished, replaced by high-rise commercial buildings. In order to standardize the spatial changes in the urban renewal process, this study introduces the concept of “Local climate zones”, which are abbreviated as LCZ. The basic types of local climate zones include built types and land cover types. One of the transformation scenarios happening at a very high rate in Changsha is that compact mid-rise building type (LCZ-2) changes to an open high-rise building type (LCZ-4), where underserved communities are now being housed in high-rise developments. Meanwhile, mixed types of LCZ (LCZ-2 and LCZ-4) is formed during the transformation.

Many researchers had explored the microclimate impact of urban renewal. For example, Li &Yu [2] analyzed the wind field around the block before and after urban renewal, concluding that buildings had different effects on the wind field in the summer and winter. Yao et al. [3] found that the high-rise building had a fundamental impact on the wind environment, and some areas around tall buildings are not benefit to the residents because of the unhealthy wind environment. Peng et al. [4] compared the original layout and planning layout of the residential area. The conclusion is that the planning layout...
had a great influence on the wind speed, which was helpful for improving thermal comfort. Researchers suggest to consider micro-climate impact in urban renewal as one of the bases for evaluating urban renewal planning. Liang et al. [5] proposed wind environment assessment methods based on CFD technology, including indicators and judgment criteria for old city renewal. Cárdenas et al. [6] studied the shadows produced by a skyscraper in urban renewal areas and its impacts for neighbour buildings, suggesting that solar access for nearby housing should be taken into consideration. There were, however, few studies compared the green space with residential redevelopment cases as urban renewal choices.

The study firstly analyzed the impact on urban wind and thermal environment during the removal and reconstruction of residential buildings using ENVI-met. Secondly, the correlation between wind and the thermal environment with building arrangement, building density, building height and green ratio in 7 ideal cases were studied. Thirdly, the Physiologically Equivalent Temperature (PET) index was simulated by RayMan to assess thermal sensation. Finally, a case study of Changsha was simulated, where a factory was reconstructed to residential buildings to check if the case study has a similar result with ideal cases. In this study, \( T_a \) represents air temperature, \( W_v \) expresses wind velocity, \( H_u \) means humidity and \( MRT \) indicates mean radiate temperature.

2. Methods

2.1. Selected thermal index

Commonly used thermal comfort indicators include Predicted Mean Vote Index and Predicted Percentage Dissatisfied Index (PMV-PPD), Effective Temperature (ET), Standard Effective Temperature (SET*), Universal Thermal Climate Index (UTCI), OUT SET and Physiologically Equivalent Temperature (PET), etc. Among them, PMV, ET, and SET* are indicators based on a stable indoor environment, which have limitations when using outdoors. OUT SET and PET are thermal comfort indicators based on outdoor conditions [7], PET is defined using the concept of equivalent temperature: it is the air temperature of a typical indoor room generating the same core and skin temperature as the actual complex outdoor conditions [8]. Residents in different climate zones have different thermal requirements.

2.2. Boundary settings

ENVI-met is a three-dimensional dynamic microclimate model developed by Michael Bruse (University of Mainz, Germany) that simulates the interaction of solid surface-vegetation-air in urban environments. The ENVI-met model can achieve 0.5~10m spatial precision and 10s-time precision. The dynamic microclimate cycle of 24~48h can be calculated based on fluid mechanics and thermocouples in ENVI-met. In this research, the extreme hot day of the whole year --July 21, 2018 of Changsha was chosen as the simulation day. The whole simulation process needs an initial climate data as the input data, which is from Mapoling weather station (National Meteorological Information Centre, 2018) [9]. The simulation started from 6:00 in the morning. At 6:00, the temperature is 31.5°C with wind velocity 3m/s and wind direction 150° (southeast direction), which were used as input data.

RayMan software is a radiation and bioclimatic model developed by the School of Meteorology, University of Freiburg, Germany. It was used to calculate the sky view factor and human physiological equivalent temperature (PET) in this study. The input parameters include: date, time, geographical location, altitude and other basic time and space information. Meteorological parameters include air temperature, humidity, wind speed, cloud amount, surface temperature, mean radiation temperature. Human physiological parameters consider clothing and activity levels, gender and height. The input meteorological parameters are simulation results from ENVI-met, and the human physiological parameters are a short-sleeved (cloth=0.5) 1.75-meter male.
2.3. Model settings

In Figure 1(a), we created a 500m×500m block sample area with 5m×5m grid size in ENVI-met software. Considering the boundary area where microclimate was affected [10], a 150 m×150 m area was renewed located in the centre. As concluded above, the urban renewal scenario that compact mid-rise building type (LCZ-2) changing to an open high-rise building type (LCZ-4) happened at very high rate. In that case, the model form of the benchmark case (500m×500m area) is based on LCZ-2, which was described as high-density, low-rise buildings (3–9 floors) with few or no trees and the underlying surface is asphalt pavement [2].

From our investigation of several old residential community in Changsha, the building plane size could be set as 60m×15m, which is a common size of building in that period. The renewed area (150m×150m) was based on LCZ-4, which represents the open arrangement of tall buildings with tens of floors. The area had both pervious land cover (low plants, scattered trees) and concrete construction materials [2].

![Image](https://via.placeholder.com/150)

**Figure 1.** (a) Cases setting; (b) Comparison of measured and simulated values; (c) Correlation analysis.

In Figure 1(a), case F and case V represent the state before renewal, and the under-renewal state respectively. The 7 cases, represent the state after renewal, discussing the building height (36m, 63m), building density (15%, 20%), and green ratio (30%, 60%) under the extreme hot summer condition of Changsha. By looking into Chinese National Regulations (GB 50180-93, 2016 edition) and Urban Planning Technical Regulations of Changsha (2016 edition), the green ratio (GR) requirements for the residential area were almost the same (no less than 30%). In order to compare the green ratio in the residential area (30%) and the green space (GR>60%), the green space of residential cases was set in strips around the buildings covered by grass, whereas the green space was covered by grass in the centre of the renewed area. The sensitivity test of ENVI-met software is needed before the simulation. By comparing and correlating the simulated and measured 24-hour Ta on July 21, 2018, Figure 1(b) (c) confirmed the correspondence between the measured and simulated data (R2=0.671), proving the research can be performed.
3. Results

3.1. Renew process
In order to examine the thermal condition variations of the renewed site and its surroundings during the entire redevelopment process, the simulation data of the original state, the current state, and renewed state at 14:00 were compared using ENVI-met. In the ENVI-met model, 9 “receptors” (Figure 2a) were set to record hourly values of the temperature humidity, solar radiation, wind speed and other meteorological indicators. The $T_a$ and $W_v$ are the average values of the 9 receptors. The wind velocity fell by 1.02m/s at the dominant wind direction (southeast), but went up to 0.75m/s on the northwest side. After the removal of buildings, the wind velocity of the target area sharply increased (1.95m/s), while the neighbouring environment was reduced by 0.3m/s. Also, the $W_v$ increased within the 50m range of the dominant wind direction (0.45m/s). After the completion of the high-rise building, the block turned to be a mixed type of LCZ-2 and LCZ-4. The central space is mostly wind-shaded and experience low air movement between buildings (reduced by 1.68m/s). It’s worth noting that the $W_v$ of the boundary between renewed area and surroundings was grown by 1.08m/s, further increased 0.23m/s within 100m around.

![Figure 2](image)

**Figure 2** (a)The location of 9 receptors; (b) $W_v$ difference between original and vacant state; (c) $W_v$ difference between vacant and case R2; (d) $W_v$ difference between original and case R2.

3.2. Cases comparison
In order to further analyzed the spatial distribution difference of the wind and thermal environment among 7 cases which are case R1, R2, R3, R4, R5, R6 and G (Figure 1a), four representative times were selected to obtain wind and thermal simulation results during the daytime (8:00, 14:00) and night (18:00, 22:00) on the referring day. 14:00 is the hottest hour in summer, 8:00 and 18:00 are the commute hours and 22:00 is three hours after sunset.

At 8:00, when the building height raised from 36m to 63m, the average $T_a$ of all residential cases dropped 0.05k on the west side pedestrian. However, when the building density increased from 15% to 25%, $T_a$ hardly changed, because the shadow area didn’t increase. The difference between the linear case R1 and the green space case G was the largest among all (0.2k) at 14:00. With the increase of building height, the air temperature decreased in the morning in summer, and the average surface...
temperature also showed a downward trend. At 18:00, the $Ta$ difference of all the cases was reclined, showing that the variables (BD and BH) had less effect on $Ta$ during the early hour at night. While the opposite results at night, an obvious $Ta$ difference appeared between the linear residential cases R1 and the green case G changed from negative (-0.2k) to positive (0.04k) at 18:00, and the difference was further increased (0.15k) at 22:00, affecting the neighbouring district 80-100m.

When the building height increased in the enclosed layout (case R5), the average $Wv$ in zone1 increased 1.2m/s, while that of linear layout case R2 decreased by 1.1m/s, with zone2 decreased 0.2m/s in the leeward side as well. It indicated that the average building height affects the ventilation inside the area. When increasing the building density, the average $Wv$ in the case R6 rose 0.7m/s, with the wind speed of surrounding 100m declined by 0.2m/s, while the $Wv$ did not change much in linear case R3. The study selected PET as an indicator for evaluating outdoor thermal comfort, calculating via RayMan Pro using outdoor physical variables. Air temperature, relative humidity, wind speed and mean radiation temperature were received at every receptor(Figure 2a) to calculate PET. The average PET calculate formula is

$$AVE \ PET = \frac{\sum_{i=1}^{n} PET_i}{n}$$

Where, n means the number of receptors.

![Figure 3. (a) PET at 14:00 & 22:00; (b) Average PET in the neighbourhood at 14:00; (c) Average PET in the neighbourhood at 22:00.](image)

In Figure 3, people's thermal perception had been evaluated on 5 scales, which are “very hot”, “hot”, “warm”, “slightly warm”, “comfortable” and “slightly cool”. The results showed that while other cases were in the “hot” zone (35°C–40°C), the green space case G had the worst outdoor thermal sensation (in “very hot” zone) at 14:00. In contrast, all the cases were in the “comfort” zone (20°C–25°C) at 22:00, except for G the lowest (23°C). In Figure 3(a), the PET of enclosed residential cases (R4 and R5) was higher than that of linear cases (R1 and R2) by (0.5°C–1°C) both during the day and at night. In the daytime, when the building height increased 27m in the linear case (R1), PET decreased 0.9°C. Similarly, as building density grew by 5%, PET declined 0.2°C. On the contrary, when increased the building height and density in enclosed cases (R5 and R6), PET grew by 0.2°C and 0.5°C respectively, which was explained by the comfort was significantly affected by mean radiation temperature. The PET difference between day and night in case G was the largest ($\Delta PET=28^\circ C$),
indicating that the night-time radiation dissipation of the green space case was significant. Figure 3(b)(c) showed the PET average value (zone 1, surrounding 50m, 100m, and 150m) on the pedestrian height (1.5m) at 14:00 and 22:00 in each case.

The PET value at 14:00 was in the range of 39.5°C to 42°C, with only PET of green space case reaching up to 50.5°C. When the building height was increased in the linear and enclosed cases, the PET within surrounding 50m were reduced by 0.5°C and 0.2°C respectively. Likewise, when the building density growing, the PET values of the linear and enclosed cases were decreased by 0.3°C and 0.1°C respectively. On this account, the growth in building height showed more effective in cooling in surrounding 50m. Within the neighbouring 100m, the PET values were reduced less (0.3°C and 0.1°C respectively).

4. Case study

A case study was simulated in order to prove the ideal case results. The site we chose was part of Shazitang community, which had similar spatial layout and size with ideal models above. The Shazitang community was a typical example located in Yuhua district, Changsha City (113E.28N). It was one of the earliest residential communities in Changsha, which was built in the early 1960s. It has 111 residential buildings of high density. Every building is tightly tied together, and the shortest distance in between was only about 3m wide. Since the original factories and state-owned staff buildings had relocated, leaving a large area to revitalize. Among all the ideal cases, R2 (BH=63m, BD=15%, GR=30%) get the best PET results on 14:00. According to the results, the renewed area with BD 15%, average BH 63m, average SVF 0.45 and 30% green ratio were designed. Buildings in neighbour distance were arranged in the north-south direction, with a floor area ratio of 1.68, building density 28%, the average height of 15m, sky view factor 0.64, and low green ratio. The simulation was on the same referring day (July 21, 2018). From the ENVI-MET results, the Ta of vacant lots and the nearby northwest pedestrian was extremely high (38.35°C) at 14:00, which further affected the neighbouring environment in the northwest direction (100m). After the high building construction, it produced a large area of shadow at 14:00, reducing Ta (35°C) between the newly-built buildings and the northwest direction neighbourhood. It was even lower than the formal pattern (36.68°C). The comparison found that the high-rise building layout mode adopted by the update scheme increases the local wind speed, making the external airflow more complicated, and in the static wind condition, it is beneficial to improve the surrounding thermal comfort. Regarding relative humidity, the average value of the renewed pattern was the highest (48.45%), followed by the former pattern (44.85%), with the vacant state the lowest (42.94%).

The 24-hour simulation results followed the ideal model results on the whole. Figure 4(a) indicated that the Ta of vacant lots between 12:00 and 17:00 was higher than that of former state and renewed state, whereas the hourly Wv showed a notable difference in the three states (Figure 4b). In general, the thermal comfort improved after redevelopment during the daytime according to Figure 4(c). However, it was worth noting that PET value getting higher (ranged from 36.2°C -53.7°C) during the vacant state (from 9:00-18:00), and further influenced surroundings with 50m. This may affect people’s daily life in the neighbourhood during the extremely hot summer of Changsha. As the neighbouring distance increased, the thermal impact of the renewed site was slighter, and can be ignored in the range of 100m-150m in Figure 4(d)(e)(f).

5. Discussion

5.1. Design strategy for outdoor public spaces

According to the above results, the following strategies are given for the thermal comfort optimization in urban renewal. 1) Reduce the enclosure degree of new residential buildings on the dominant wind direction in order to improve the ventilation and heat dissipation. Moreover, adopting a stepped structure or staggered layout of buildings allows wind to pass through the aisles in-between, thus maximize the heat dissipation of the internal space. For the enclosed building layouts, appropriate
green space is encouraged. 2) The building layout should take advantage of its shading to reduce the intense solar radiation in the summer. 3) The green space redevelopment mode has a better cooling effect than the residential case at night, helping to alleviate the heat island effect in the neighbourhood level. Also, research showed the cooling effect of green space also depends on the actual size of it [11]. Overall, the study shows that urban renewal will lead to changes in outdoor thermal comfort. Both high-rise residential and green space redevelopment will improve the outdoor thermal comfort to a certain extent, and the impacts could reach 100m around.

Figure 4. (a) Hourly $T_a$ comparison of three states; (b) Hourly $W_v$ comparison of three states; (c) Average PET comparison of three states; (d) Average PET at former state; (e) Average PET at vacant state; (f) Average PET at renewed state.

5.2. Limitations and future work
The present study focuses on the microclimate and thermal comfort change during the urban renewal process in summer. Simulation of different seasons would help better understand the relationship between spatial elements (building height, building density and building layout) and microclimate. Moreover, the current simulation doesn’t include trees, which would provide shadows in hot summer [12]. The arrangement, species, size of trees have influence on the microclimate. Several more cases would be needed to classify the impact of trees.

6. Conclusions
The simulation results from both the ideal cases and the experimental case confirmed the hypothesis that significantly different thermal comfort conditions existed within the renewed area and its neighbourhood (distance of 100m). Even though the thermal comfort threshold of the ideal cases and the experimental case are different, they follow a similar trend in the renewal process. 1) During the renewal process, the $W_v$ of the ideal model and the empirical case was significantly climbed to 1.95m/s and 1.7m/s respectively at the vacant state in the daytime. At the meantime, the average $W_v$ in
the surroundings was reduced by 0.3 m/s and 0.2 m/s. The reason owing to adding high buildings brought up terrain roughness of the whole block, therefore, the airflow cannot be introduced into the new building area and the leeward side pedestrians, forming wind-shaded zones. Strong turbulence within 50 m appears at opposite sides of the windward side. 2) High-rise urban renewal mode, although not conducive to internal site ventilation (reduced 1.68 m/s in ideal case and 1.0 m/s in the empirical case), cast shadows that reduce the mean radiation temperature, relieving the high outdoor thermal sensation at pedestrian height during the day. 3) Case G had much higher PET (10°C -11°C) during the day and a lower PET value (0.5°C-1°C) than other cases at 22:00, which provided cooling in the summer night. The cooling impact of green space would affect the surrounding area 50 m from its boundary in this study. The extreme PET during the day may owing to lack of shadows. 4) The linear cases had better PET value than the enclosed cases (0.05°C-0.13°C lower), mainly due to its better ventilation. 5) The increase in building height was more conducive at the optimization of outdoor thermal comfort than building density because adding building density create larger proportion of the wind-shaded areas.

Acknowledgment
This study is supported by the National Natural Science Foundation of China (No. 51608535), and the Fundamental Research Funds for the Central South University (No. 502221805)

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