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Research on Urban Heat-island Effect

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Abstract

Urban heat island (UHI) effect is a kind of heat accumulation phenomenon within urban area due to urban construction and human activities. It is recognized as the most evident characteristic of urban climate. The increase of land surface temperature caused by UHI effect will definitely influence material flow and energy flow in urban ecological systems, as well as alter their structure and functions, exerting a series of ecological and environmental effects on urban climates, urban hydrologic situations, soil properties, atmospheric environment, biological habits, material cycles, energy metabolism and residents' health. Through the improvement of energy efficiency, urban landscape optimization, green roof construction, high reflectivity material utilization and green land cultivation, UHI effects could be significantly mitigated. Based on remote sensing technology and numerical simulation methods, research on the ecological and environmental effects of UHI has been multi-scaled conducted, providing theoretical reference for the improvement of urban ecological environment and realization of urban sustainable development.

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1. Introduction

Urban heat island (UHI) effect is widely recognized as a heat accumulation phenomenon, which is the most obvious characteristic of urban climate caused by urban construction and human being activities [1,2]. In early 19th century, scholar Lake Howard firstly measured and discussed UHI effect when studying urban climate in London, England. Since then, many scholars around the world conducted deeply research on the characteristics of UHI effect

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[3-6], reaching that UHI effect has close relationship with urban heat release, properties and structure of underlying surface, vegetation coverage, population density and weather conditions. Meanwhile, the scale and intensity of UHI effect will be increasingly serious with the on-going urbanization. It is studied that UHI effect of Szeged and New York are 3.1°C and 8.0°C respectively [7]. Meanwhile, it is found that China is also experiencing severe UHI effect in many modern cities, especially the average temperature difference on the outskirts of Beijing reaches 3.3°C from 1961 to 2000, and UHI effect of Shanghai reaches 7.4°C [8,9]. Urban temperature, especially surface temperature, is the energy balance center of urban surface and one of the most important factors affecting urban climate, regulating and controlling various ecological processes [10-12]. However, the increasingly intensive urbanization has led to the constant increase of surface temperature, definitely resulting in altering of urban resource and energy flow. More importantly, the structure and function of urban ecological system will also be changed, affecting urban residents' health [13,14]. In addition, UHI effect has received great attention from urban meteorologists. However, due to the complexity of the research object, few researches on ecological and environmental effects caused by UHI effect has been so far conducted from the perspective of ecosystem.

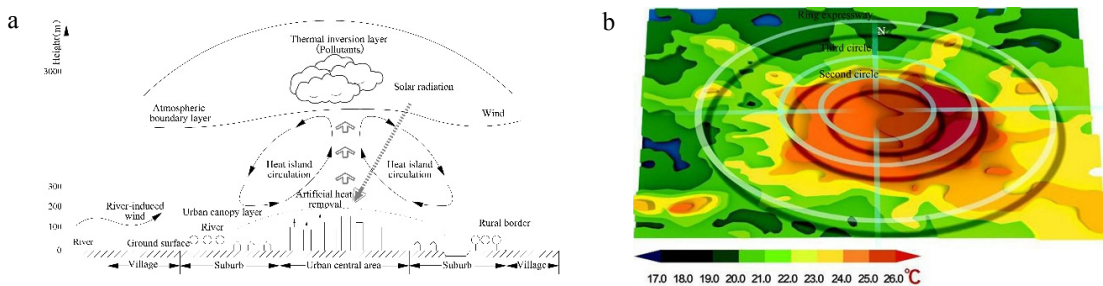


Fig. 1. (a) Urban heat island (UHI) effect; (b) The numerical simulation of UHI effect.

Taking Bozhou industrial park as a research case, this article has numerically simulated urban thermal environment in summer based on digital technology, aiming to provide theoretical reference for the future urban planning and spatial arrangement. Specifically, Computational Fluid Dynamics (CFD) technology is introduced into numerical experiment, computer simulation and analysis research to discuss urban thermal environment under the influence of climatic environment.

2. Meteorology Condition Analysis of Bozhou, China

It is essential to research the typical climatic conditions of Bozhou in summer as the initial simulation conditions before the numerical simulation to urban thermal environment. Bozhou is located at 31°14'N, 121°29'E, adjacent to Yangtze River Delta, as shown in Fig. 2(a). Bozhou is in the hot summer and cold winter climate zone with characteristics of high temperature and high humidity in summer. Due to higher relative humidity, sweat within human bodies is hard to be discharged causing bad thermal comfort in summer.

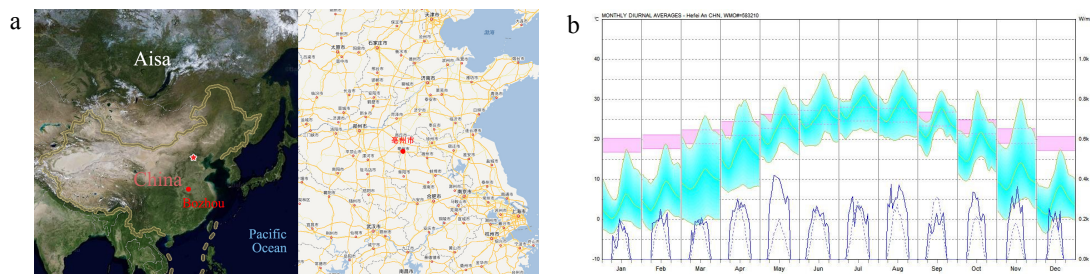


Fig. 2. (a) The location of Bozhou, China; (b) Annual mean temperature, solar radiation, thermal comfort distribution of Bozhou, China.

Based on ECOTECT software, the basic meteorological parameters including annual mean temperature, solar radiation, thermal comfort (as shown in Fig. 2(b)) and rainfall data (as shown in Table 1) have been achieved [8]. As seen from Fig. 4, it is obvious that the most intensive solar radiation in one year occurs in May, the highest temperature occurs in June, the mean highest temperature occurs in Jul with 28°C. Therefore, the July with highest mean temperature is selected as the simulation month. Fig. 3 shows the wind direction, wind frequency and wind speed distribution in noon (10.00-14.00) in July, Bozhou. In July, Bozhou mainly experiences south wind, southeast wind and southwest wind, with the highest wind speed of 50 km/h and mean wind speed of 15 km/h. Based on the statistic results by ECOTECT, in simulation, the wind is determined as southeast wind with wind speed 15km/h and temperature 28°C.

Table 1. Meteorological data of Bozhou, China

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Temperature (°C)	0.6	3.1	8.2	15.3	20.7	25.5	27.3	26.4	21.6	15.7	8.7	2.7
Mean highest temperature (°C)	5.9	8.6	13.8	21.4	26.8	31.2	32	31.1	27.1	21.9	14.7	8.3
Extreme highest temperature (°C)	22.6	24.9	28.7	34.9	39.1	41.3	40.4	38.5	37.0	35	29.9	21.1
Mean lowest temperature (°C)	-3.4	-1.2	3.4	9.8	15.1	20.2	23.4	22.6	17.2	10.9	4.1	-1.5
Extreme lowest temperature (°C)	-14.3	-14.9	-8.5	-2.6	3.9	11.6	16.6	15.5	6.2	-1.2	-8.8	-17.5
Mean rainfall (mm)	16.4	21.1	37.4	43.8	69.3	101.9	204.1	131.1	71.8	53.5	25.8	13.9
Precipitation days (day)	4.1	5	6.8	6.5	7.6	8.5	12.2	10.5	7.8	7.0	5.4	3.9
Mean wind speed (m/s)	2.4	2.6	2.9	3.0	2.7	2.5	2.3	2	2.0	2.1	2.3	2.4

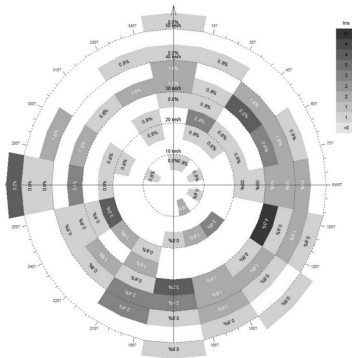


Fig. 3. Wind direction, wind frequency and wind speed distribution in noon (10.00-14.00) in July, Bozhou, China.

3. Establishment of CFD Model

Complex urban model should be imported into CFD numerical model for calculation once the initial conditions of external environment are set. In general, city is a complicated research object as well as an integration of a variety of information, thus it is a very arduous task to reflex all data and materials [15, 16]. Therefore, this article has only considered urban properties related to urban thermal environment rather than secondary causes, having same characteristic of little impact on thermal environment. According to the current urban texture, urban area is simplified as various blocks with distinctive boundaries separated by main road, commercial zone, public architecture, afforestation and river system. All these blocks are defined with corresponding properties in terms of land use ratio, population density, building density, plot ratio and afforestation rate [17-21]. Fig. 4(a) has shown the land use planning of main urban area of Bozhou, China from 1999 to 2000, while Fig. 4(b) shows its main function divisions. The layout of public space follows the principle of “One main area and four secondary areas”, in which the one main area means downtown area (including main commercial area) and four secondary areas refer to surrounding four sub-central areas

(including residential districts, administration center, logistic storage and school). All these areas have the features of high building density, large volume fraction and high population density.

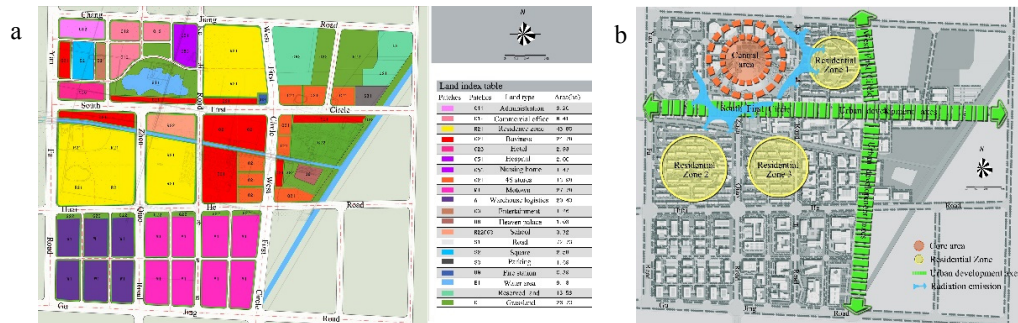


Fig. 4. (a) Land use planning of main urban area of Bozhou, China (1999-2020) ; (b) Area functional division of Bozhou, China.

According to some research, at certain wind speed, urban ventilation effect is not obvious when the ventilating duct is less than 100 m and only when the duct is more than 150 m can the urban area achieve ideal heat and ventilation effects [22, 23]. With regard to grass land, ecological function of reducing surface temperature tends to be notable when the grass land dimensions are larger than $120 \text{ m} \times 120 \text{ m}$. Therefore, the CFD model has taken relatively larger park and grass land into consideration rather than small ones. In addition, the CFD model has divided blocks into five categories according to building density, plot ratio, green area and population density, as shown in Fig. 5(a).

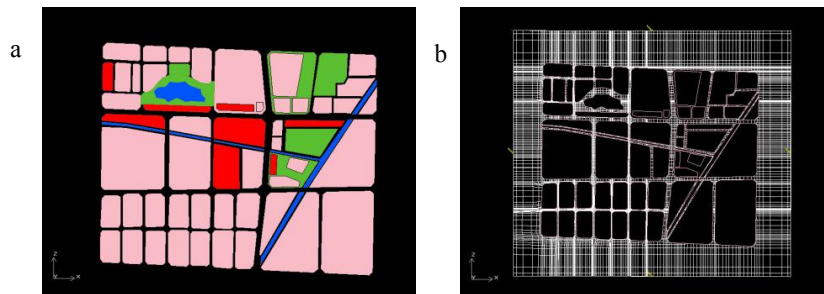


Fig. 5. (a) CFD numerical division of urban area of Bozhou, China; (b) CFD grid generation of Bozhou, China.

It is well known that meshing grid exerts significant influence on calculation precision and stability [24, 25]. In the CFD numerical simulation, unstructured grid technique is employed to separate urban model with various shapes, so as to maximum express urban complex city underlying surface, as shown in Fig. 5(b), improving simulation effects. Unstructured grid is not restricted by the topology of solution domain and boundary shape, conducive to build up models. Meanwhile, it is beneficial to generate adaptive grids, with characteristic of automatically adjusting the grid density according to flow fields, effectively improving the calculation precision of the whole area.

Overall consideration the influence of solar radiation and wind speed over a block model, the attribute parameters, such as building density, plot ratio, green area and population density have been endowed on different levels of block zones [26]. Block type is settled as fluid and water material when it comes to 5th zone (including urban rivers and lakes). Meanwhile, due to the solar radiation and water evaporation, an opening with the same area as water surface is set for up-going wind. According to field test materials, the initial temperature of wind is 25°C . As for 4th zone (grassland), its latent heat storage capacity is greater than sensible heat due to less vegetation thermal radiation ability than building surface and larger heat capacity, having positive meaning to enhance urban thermal environment. The property of block is set as hollow with initial tested temperature of 26°C . Compared with the 1st zone, the 2nd and 3rd zones are mainly residential areas, having relatively lower traffic flows and higher greening rate. Therefore, these are set as hollow block and brick materials with initial temperature of 30°C . However, the 1st zone has the highest

traffic flow and highest building density, thus the property is set as solid with cement texture and 40°C initial temperature. Based on this, solar radiation and wind environment have been settled according to wind direction, wind speed and mean temperature in July shown in ECOTECT. In terms of solar radiation, the longitude and latitude of Bozhou, China have respectively determined in CFD model, at the noon on July 15. The sun incidence coefficient and the ground reflectance are 1.0 and 0.2, respectively. In addition, air flow is set as turbulent under RNG model, with one standard atmospheric pressure.

4. Influence Factors of UHI Effect

Atmospheric environmental meteorological parameters, such as temperature, humidity, air flow and radiation, determine the outdoor climatic conditions [27]. In general, thermal and humidity index (THI), relative stress index (RSI) and Beer Garden day (days when temperature higher than 20°C at 21.00) are used to evaluated weather adaptability, in which THI is the most widely adopted with the definition as follows.

$$THI = T - (0.55 - 0.0055H) \times (T - 14.5)$$

Where T means the maximum temperature, H means relative humidity.

THI is used to identify the un-comfort level of human body towards hot and cold environment, as shown in Table 2. When the THI index is between 15°C and 20°C, it is thought as the most comfortable environment. While THI is less than 15°C, the water evaporation will bring heat from the skin, people will feel cold; while the THI is larger than 20°C, people will feel hot and sweat. It is researched that UHI effect in urban center is more severe than that in outskirt. In hot summer, high temperature will make people unpleasant, resulting in the reduction of living quality as well as working productivity [28]. Meanwhile, UHI effect would make urban pollution more severe, affecting citizens' health. Research has found that citizens living in urban areas with UHI effect suffer digestive system disease [29], typically performing less appetite and indigestion with high reoccurrence rate. In addition, citizens in UHI areas are suffering from nervous system disease with insomnia, irritability, depression and memory decline.

Table 2. The thermal and humidity index category

THI category	THI (°C)
Hyper glacial	< -40
Glacial	-39.9 - -20
Extremely cold	-19.9 - -10
Very cold	-9.9 - -1.8
Cold	-1.7 - +12.9
Cool	+13.0 - +14.9
Comfortable	+15.0 - +19.9
Hot	+20.0 - +26.4
Very hot	+26.5 - +29.9
Torrid	>+30

5. Results Analysis of Thermal Environment

Through the numerical simulation, the temperature, wind speed, air age and solar radiation distribution of Bozhou, China have been obtained under typical conditions in the noon (10.00-14.00) in July. Based on comprehensive comparison, the relationship between urban planning and urban climate in Bozhou has been concluded. As shown in Fig. 10, wind distribution of Bozhou has been obviously seen under the influence of southeast wind. In summer, the urban center experiences the highest temperature, while the municipal sub center suffers relatively lower, as the red zone and yellow zone in Fig. 6(a). In general, the temperature in downtown is clearly higher than that of surrounding areas, forming the distinctive UHI effect. In the main urban center, temperature decrease along with the level of urban

zones. Especially, the temperature in rivers and lakes is relatively lower than other areas, thanks to the water evaporation and ventilated corridor.

Fig. 6(b) shows the wind speed over main city, and it is easy to investigate wind distribution. Due to the influence of urban texture, although wind direction keeps constant when flowing over urban area, wind speed reduces greatly. This is indicated by lower speed at urban backward position. Seen from wind speed (Fig. 7(a) and Fig. 7(b)) and air age (Fig. 8(a) and Fig. 8(b)), wind speed at outskirts is relatively higher with shorter air age, indicating wind stands for a short time around urban areas. However, wind in central urban area is blocked by surrounding building, showing a lower wind speed and longer air age. Meanwhile, obvious wind shade area has been observed at the backward of urban center, and air age is relatively short in some streets with the same direction as wind.

In addition, through the above comparison, wind over the city has been affected by urban texture, although it has not been influenced by lower buildings. It shows that wind speed decreases and air age increases, whereas the influence will decrease along with height. Through numerical simulation, it is concluded that UHI effect is caused by both the change of underlying surface and less ventilation. However, with the improvement of ventilation situation, overall temperature of urban area with UHI effect shows a trend of decrease. Compared with the field test results, CFD numerical results are consistent. Central area (including commercial areas and entertainment area) in Bozhou has witnessed a significant change of underlying surface, building density and population. At the same time, it is affected by longer solar radiation and poorer air flow. All these factors have been accumulated to generate UHI effect. Around urban rivers, rivers as well as large grassland, UHI effect has been alleviated, thanks to the climatic regulation effects of water and vegetation.

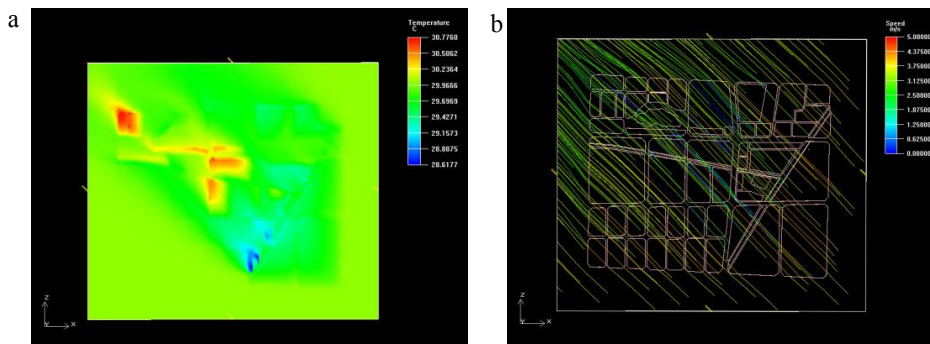


Fig. 6. (a) Temperature distribution over Bozhou City, China; (b) Wind speed line in Bozhou City, China.

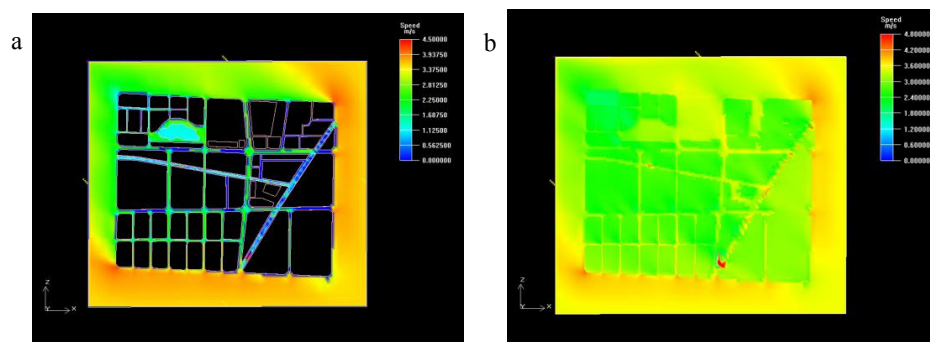


Fig. 7. (a) Wind speed distribution in Bozhou City, China; (b) Wind speed distribution over Bozhou City, China.

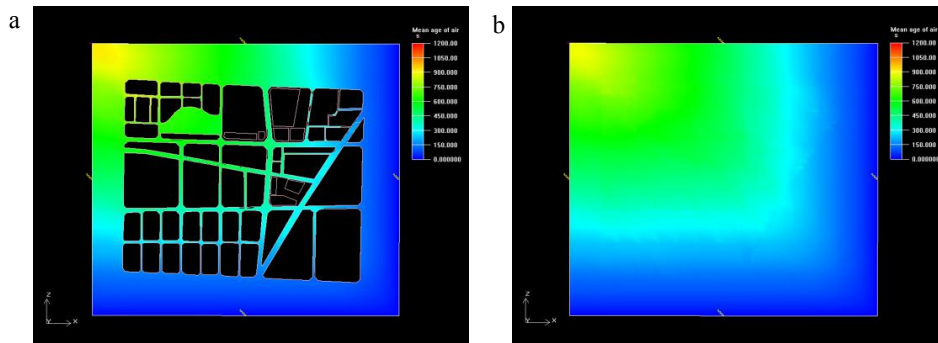


Fig. 8. (a) Air age distribution in Bozhou City, China; (b) Air age distribution over Bozhou City, China.

6. Conclusions

In general, rivers and lakes could improve heat transporting process and bring fresh air, so as to balance urban temperature, just as the role of river and lake system. In addition, rivers and lakes could also separate urban thermal fields, reducing thermal radiation, alleviating thermal field circulation and eliminating UHI effect. Rivers, one of the viral important parts of urban area, are expected to be closely combined into cities and play various functions. In summer, urban rivers and lakes are the main sources to reduce urban temperature in Bozhou, China. Therefore, building planning and density along rivers and lakes will directly influence the effect of wind towards urban central areas. Areas adjacent to water zone with convenient traffic is beneficial to commercial activities and climatic improvement. Meanwhile, building high-rise residential buildings could save land, changing the traditional narrow roadway in Hanzhen road.

Acknowledgements

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