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Original Research Paper

Influence of Urban Heat Island on Office Building Energy Consumption

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ABSTRACT

In order to investigate the influence of urban heat island on office building energy consumption which is located on different land use types, several representative land use types were selected in Chongqing to do continuous air temperature measurements on August 2007 and January 2008. Urban heat island intensities were obtained with the measured data. The energy consumption simulation software eQUSET was employed to simulate the influence of urban heat island on cooling loads and heating loads of office building separately. The results showed that commercial areas usually have high urban heat island intensities. Additionally, the energy consumption of air conditioning in office building would be increased by 3.48kWh/m^2 and the energy consumption of heating would be decreased by 1.22kWh/m^2 when the UHI intensity increased by 1°C.

INTRODUCTION

Increasing urbanization and industrialization has caused the urban environment to deteriorate. The urban climate and the environmental efficiency of buildings are influenced by the deficiencies in proper development control (Santamouris et al. 2001). As a consequence of changes in the heat balance, air temperatures in densely built urban areas are higher than the temperatures of the surrounding country. This phenomenon, known as the urban heat island (UHI) effect, is a reflection of the totality of microclimatic changes brought about by man-made alterations of the urban surface. UHI was first identified by Luke Howard in 1818 in London.

As a consequence of increased temperature, the UHI has an effect on energy consumption for heating and cooling urban buildings. This has been studied internationally including Europe, Japan and US (Santamouris et al. 2007, Ewing et al. 2008). In Athens, annual cooling energy and peak demand were investigated to estimate the effect of high temperatures on cooling energy and peak demand. Both were found to be significantly increased as a result of the urban heat island effect, highlighting the need to reduce cooling energy by natural means (Hassid et al. 2000). Kolokotroni et al. (2007) used measured air temperature data as input to a building energy simulation computer program to assess the heating and cooling load of a typical air-conditioned office building positioned at 24 different locations within the London heat island. It was found that the effect of the London heat island on energy used for heating and cooling depends on the degree of urbanization in a particular location, radial distance from the city center and the relative contribution of solar gain to total gains in a building.

Studies have also been conducted in city blocks to explore the interaction between summertime outdoor thermal conditions and cooling energy demand in urban areas. Kikegawa et al. (2003) developed a numerical simulation system adopting a new one dimensional urban canopy meteorological model coupled with a simple sub-model for the building energy analysis. This system was applied to the Ootemachi area. The simulated temperature sensitivity of the peak-time cooling electric demand in the Ootemachi area was found to be almost consistent with the actual regional average sensitivity over all business districts in the central part of Tokyo, which was estimated using actual electricity demand data provided by the Tokyo Electric Power Company. Ihara et al. (2008a) simulated the year-round air temperature and annual energy consumption in an office district in Tokyo and quantified effects of UHI countermeasures on both cooling and heating energy consumption. In addition, (Ihara et al. 2008b) analysed electricity consumption in actual office buildings and derived the sensitivity of electricity consumption to air temperature and humidity to evaluate the effect of the UHI. Nevertheless, the target area and building types were still limited in those studies. A few quantitative evaluations of the energy-saving effects of UHI mitigation have been conducted (Vu et al. 1998, Ashie et al. 1999, Kikegawa et al. 2006), but the target areas and weather conditions in these studies have been limited.

The above studies showed that the influences of the urban heat island on building energy consumption should not be neglected. However, heat island intensity differs in different parts of the city, which means the UHI intensities were related to different land use types. Few studies focused on the influences of UHI on building energy consumption associated with land use types in urban areas. Therefore, this paper extends this study and focuses on UHI intensities in different land use types and the influences of UHI on office building energy consumption.

URBAN HEAT ISLAND MEASUREMENTS

Overview of the measurements: Land surface and land use types were complex in urban areas. Land use types such as streets, squares, green lands, waters and so on contribute to the surface energy balance in the city. In order to find out the characteristics of ambient thermal environment of different land use types and their differences, several representative land use types were selected to do continuous air temperature measurements on August 2007 and January 2008.

In the measurement of August 2007 (summer measurement), seven representative observation points were selected and the corresponding land use types were suburbs, Ciqikou Old Town (cultural area), Station Road apartment (residential area), lawn of Chongqing University Area A (campus area), residential of Chongqing University Area C (residential area), Shayang Road (street area) and Huayu Plaza (commercial area). In the measurement of January 2008 (winter measurement), five representative observation points were selected and the corresponding land use types were suburbs, residential area of Baimahan (residential area), Chongqing University Area B (campus area), Xinyang Plaza (commercial and residential area) and Chenjiaping commercial center (commercial area).

The instruments included automatic temperature and humidity data loggers (HIOKI 3641) and a GPS data logger (GlobalSat DG-100). The automatic temperature and humidity data loggers were made in Japan with the accuracy of 0.5°C (0.0°C-35.0°C). The GPS data logger was made in Taiwan with SiRF star III wafer. The activation time of all the instruments were set to be coincidence with the observation time, and the record intervals were set 5 minutes. The automatic temperature and humidity data loggers were put in the thermometer screen, which were fixed at about 1.5 meters high above the ground.

Results of the summer measurement: Diurnal changes of UHI intensities at each observation points in summer are shown in Fig. 1. Maximum and average value of UHI intensities at each observation points are given in Table 1.

It could be seen from the Fig. 1 that there was an obvious air temperature increase in urban areas compared to the suburb which indicated that the UHI phenomenon was obvious in Chongqing in summer. The UHI intensities of different land use types appeared a great difference, while the daily trends of UHI intensities were in accordance with the typical heat island diurnal variation regularity. UHI intensities in the night time were higher than that during the daytime and the maximum UHI intensities were usually obtained at about 22:00 p.m. to midnight.

As seen from Table 1, the maximum daily average UHI intensity was 3.0°C and the minimum value was 1.7°C. The order of average daily UHI intensities was as follows: Huayu Plaza > Shayang Road > residential of Chongqing University Area C > lawn of Chongqing University Area A > Station Road apartment > Ciqikou Old Town. Huayu Plaza was commercial area and there were intensive commercial activities and large anthropogenic heat emissions, which were the reasons why commercial areas usually had the highest UHI intensity value.

Results of the winter measurement: Diurnal changes of UHI intensities at each observation points in winter are shown in Fig. 2, and maximum and average value of UHI

Table 1: Maximum and average value of UHI intensities at each observation point.

Measurement sites	Ciqikou (site 1)	Station Road Apartment (site 2)	Chongqing University Area A (site 3)	Chongqing University Area C (site 4)	Shayang Road (site 5)	Huayu Plaza (site 6)
Maximum UHI Intensities	4.2	5.3	4.2	3.8	6.1	6.1
Average UHI Intensities	1.7	2.2	2.3	2.7	2.8	3.0

Table 2: Maximum and average of winter heat island intensity for each measuring point.

Measurement sites	Baimahan (site a)	Chongqing University Area B (site b)	XinYang plaza (site c)	Chengjiaping (site d)
Maximum UHI intensities	2.8	3.5	3.8	4.6
Average UHI intensities	1.2	1.8	2.2	2.3

Table 3: CDD of measurement sites.

Measurement sites	suburb	site1	site2	site3	site4	site5	site6
UHI intensity in summer	0	1.7	2.2	2.3	2.7	2.8	3.0
CDDs(26)/(°C·d)	236	395	448	457	498	512	535

Table 4: HDD of measurement sites.

Measurement sites	suburb	site a	site b	site c	site d
UHI intensity in winter	0	1.2	1.8	2.2	2.3
HDDs (18)/(°C·d)	779	679	639	620	565

intensities at each observation points in Table 2.

As seen from Fig. 2, it could be found that there were also obvious air temperature differences between urban areas and the suburban areas in winter, while the UHI intensities were lower than that in summer and the diurnal changes of UHI intensities at each observation points were similar to the summer changes.

The Table 2 shows that the maximum daily average UHI intensity was 2.3°C with the minimum value of 1.2°C. The order of average daily UHI intensities was as follows:

Chenjiaping commercial center > Xinyang Plaza > Chongqing University Area B > Residential of Baimahan.

UHI intensities in Chenjiaping commercial center and Xinyang Plaza were higher also in winter. UHI intensities in winter were lower than that in summer in Chongqing during the measurement period.

Compared to other studies of UHI intensity in Chongqing, it could be found that the characteristics of UHI during the measurement was much similar to others results. Therefore, the measurement results could be used as boundary condition input to study the influence of UHI on office building energy consumption.

Acquisition of annual meteorological data: First of all, it should be announced that the collection of meteorological data was based on the typical meteorological year data of Shapingba Weather station in Chongqing and assumed that the annual meteorological data of the suburban site was the typical meteorological year data. Then, the daily hourly UHI intensities were assumed to remain the same during the air-conditioning period in summer from May 1st to September 30th and during the heating period in winter from December 1st to February 28th the next year. Therefore, annual meteorological data could be obtained by modifying the meteorological data of each measurement points using the UHI intensities acquired during the measurements.

STATIC ANALYSIS OF THE INFLUENCE OF UHI ON BUILDING ENERGY CONSUMPTION

Cooling Degree Day (CDD) and Heating Degree Day (HDD) were two indices to study the energy consumption. CDD and HDD could be calculated using the equations below:

$$CDD(26) = \sum^{N} (T_p - T_n) \qquad ...(1)$$

$$HDD(18) = \sum^{N} (T_n - T_p) \qquad ...(2)$$

T_n was the base temperature of cooling or heating, T_p was the outdoor average temperature on someday during the cooling period or heating period, N was the cooling days or the heating days.

According to the measurement data, the CDD and HDD could be calculated as given in Tables 3 and 4.

It could be seen from Tables 3 and 4 that CDD would increase when UHI intensity increased and HDD would decrease when UHI intensity increased. Compared with the changes of CDD and HDD with UHI intensity, it could be predicted that UHI may influence CDD more than that of HDD.

DYNAMIC ANALYSIS OF THE INFLUENCE OF UHI ON OFFICE BUILDING ENERGY CONSUMPTION

Description of the Office Building Model

According to the climatic characteristics of Chongqing and the characteristics of most office buildings in Chongqing, an office building facing south was selected to do the simulation. The construction area was 2111m^2 with 5 stories and the height of each storey was 3.9m. The shape coefficient was 0.24. Exteriors of the building were equipped with the delighting windows and the sizes of the windows were 6.8m × 2.4m, 2.4m × 2.4m and 1.5m × 2.4m, respectively. The window to wall area ratio was 45% on the north and south sides, while the window to wall area ratio was 8% on the west and east sides. The average window to wall area ratio of the office building was 33%. The air-conditioning areas were considered as the total construction areas of the building. The model of the office building is shown in Fig. 3.

Construction and thermal properties of the envelope were as follows: Exterior wall was 200mm of hollow brick, additional 20mm internal plastering, the heat transfer coefficient of exterior wall was 1.73 W/(m^2·K); the external windows were made of a single layer of ordinary glass, the heat transfer coefficient was 4.7W/(m^2·K); Heat transfer coefficient of the roof was 1.22W/(m^2·K).

Loads and Operation Time Periods

The interior design parameters of the office buildings in summer was temperature 26°C and relative humidity 55%. The

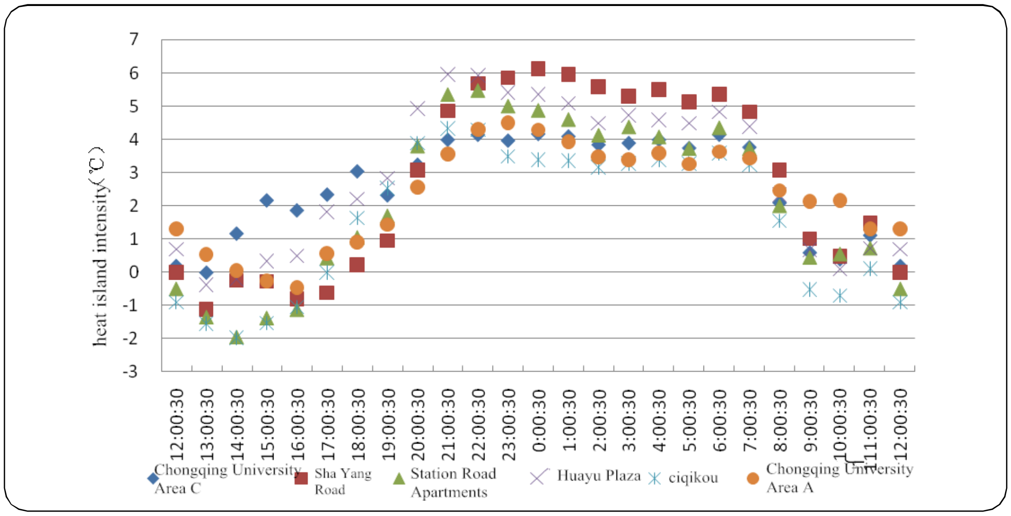

Fig. 1: Diurnal change of UHI intensities at each observation point in summer.

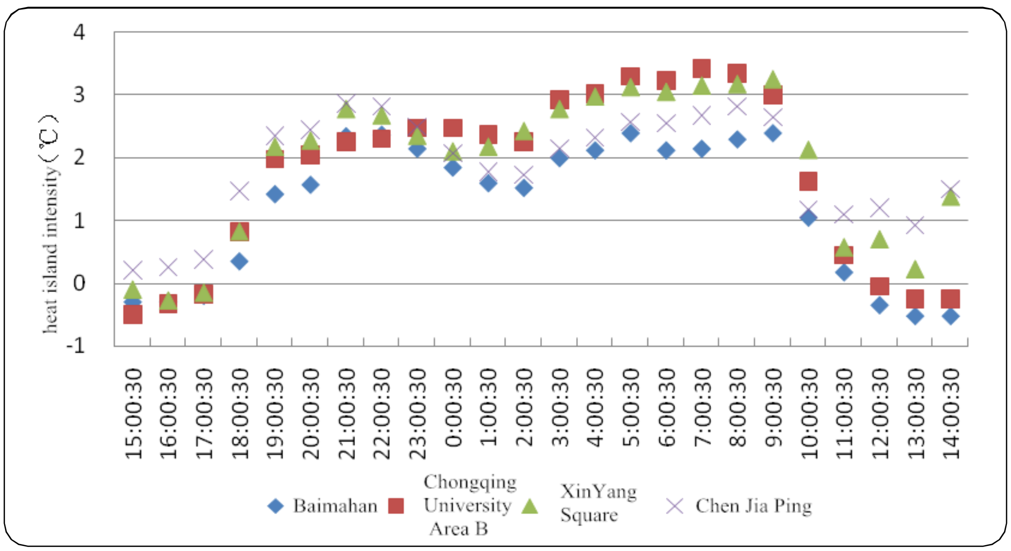

Fig. 2: Diurnal variation of winter heat island intensity of each measuring point.

interior design parameters in winter was temperature 20°C and relative humidity 50%. The density of lighting, equipment, personnel and the variation of load were set according to the specification and the typical schedule of the office buildings. According to the characteristics of office buildings, the operation time periods of air conditioning system were from Monday to Friday and from 8:00 a.m. to 18:00 p.m. every day.

Air Conditioning Systems and the Scheme of the Heating and Cooling Sources

The scheme of the air-conditioning system adopted the air fan coil mode. The total air volume of the system was obtained by the eQUEST simulation software based on the calculated heating and cooling loads. According to the design standards, the volume of the fresh air calculated was 30m^3 per person hourly. A heat pump chiller was used to satisfy cooling requirements in summer and heating requirements in winter, the equipment capacity was calculated by the software automatically based on the loads.

Results of Simulations

Influence of UHI on cooling loads of office building: The UHI intensities of each measurement sites in summer and calculated electric power of the office building are given in Table 5. The UHI intensities were the average value during

Table 5: UHI intensities and electric power consumption of measurement sites.

Measurement sites	suburb	Site1	Site2	Site5	Site6	Site3	Site 4
UHI intensity (°C)	0	0.04	0.15	0.29	0.8	0.96	1.37
Electric power consumption (kWh/m^2)	0	0.17	1.01	1.35	2.66	3.30	4.75

Table 6: Influence of UHI intensities on energy consumption of air conditioning.

Measurement sites	suburb	Site 1	Site 2	Site 5	Site 6	Site 3	Site 4
UHI intensity (°C)	0	0.04	0.15	0.29	0.8	0.96	1.37
Electric power consumption (kWh/m^2)	0	0.17	1.01	1.35	2.66	3.30	4.75
Increase rate	0	0.5	2.9	3.9	7.6	9.4	13.6

Table 7: Influence of UHI intensities on energy consumption of heating.

Measurement sites	suburb	site a	site b	site c	site d
UHI intensity (°C)	0	0.37	0.70	1.75	2.67
Electric power saved (kWh/m^2)	0	0.96	1.38	2.40	2.91
Decrease rate(%)	0	8.7	12.5	21.8	26.5

the operation time periods. It could be seen that the higher the UHI intensity was, the more of the electric power consumption. At the residential area site 4, its average UHI intensity was 1.37°C, which caused the electric power consumption increased; the same increase also happened at other five sites.

If the simulation result of the suburban area was selected as the baseline, the increase of the electric power consumption caused by UHI could be calculated (Table 6).

It could be seen from Table 6 that energy consumption of air conditioning increased with the enlargement of the heat island intensity. At site 4, where the maximum heat island intensity was, the energy consumption of air conditioning had increased by 4.75kWh/m^2, the increase rate was 13.6%. While at site 1, where the heat island effect was inconspicuous in summer, its energy consumption increased and the increase rates were 0.17kWh/m^2 and 0.5% respectively.

With the calculated and simulated data, the relation between energy consumption increase and UHI intensities could be found by linear regression (Fig. 4). It could be seen from Fig. 4 that the increase of energy consumption of air conditioning in office building in Chongqing would be 3.48kWh/m^2 when the UHI intensity increased by 1°C, which means that the energy consumption of air conditioning would

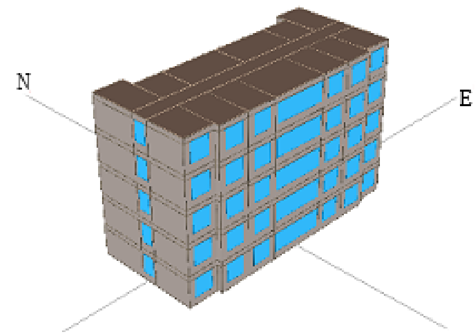

Fig.3: Model of the office building.

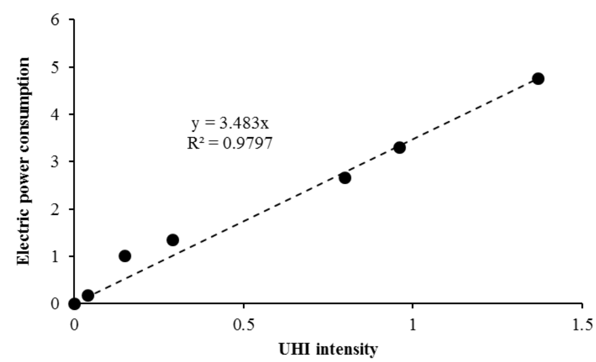

Fig. 4: Regression of UHI intensity and electric power consumption.

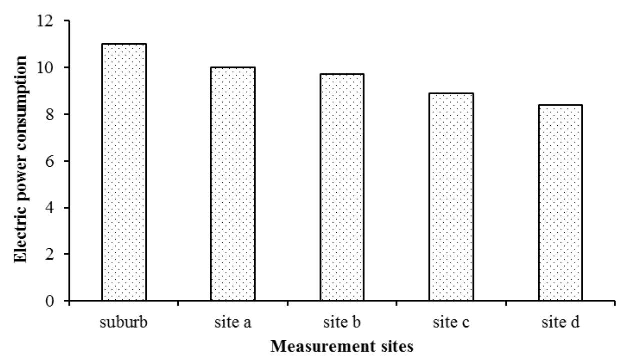

Fig. 5: Electric power consumption of measurement sites.

increase by 9.9% when the UHI intensity increased by 1°C.

Influence of UHI on heating loads of office building: The calculated electric power consumption of the office building is shown in Fig. 5. It could be seen that the air temperature in each site in urban areas was higher than that in suburban area and the electric power consumption decreased when UHI intensities increased.

If the simulation result of the suburban area was selected as the baseline, the decrease of the electric power consumptions caused by UHI could be calculated (Table 7).

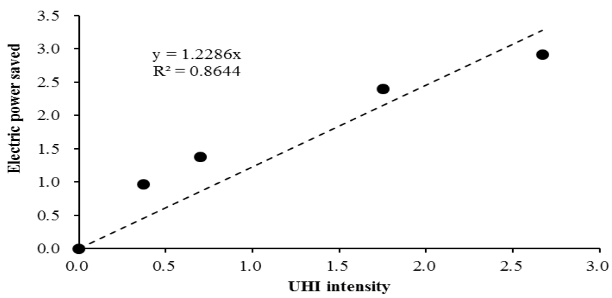

Fig.6: Regression of UHI intensity and electric power saved.

With the calculated and simulated data, the relation between energy consumption decrease and UHI intensities could be found by linear regression (Fig. 6).

It could be obviously seen from Table 7 that the higher UHI intensity was, the more was the electric power consumption. At site d, where the maximum heat island intensity was, the energy consumption of heating had decreased by 2.91kWh/m^2, the decrease rate was 26.5%.

It could be seen from Fig. 6 that the decrease of energy consumption of heating in office building in Chongqing would be 1.22kWh/m^2 when the UHI intensity increased by 1°C, which means the energy consumption of air conditioning would decrease by 11.1% when the UHI intensity increased by 1°C. Compared with Fig. 4 and 6, it could be found that the influence of UHI on energy consumption of heating in office building in Chongqing was relatively smaller than that of energy consumption of cooling.

DISCUSSION AND CONCLUSION

Commercial areas are usually UHI centers in urban areas. The maximum daily average UHI intensity was 3.0°C, and the minimum 1.7°C in summer, while the maximum daily average UHI intensity was 2.3°C, and the minimum 1.2°C in winter during the measurement time periods.

The energy consumption of air conditioning in office building would be increased by 3.48kWh/m^2 and the energy consumption of heating would be decreased by 1.22kWh/m^2 when the UHI intensity increased by 1°C, which showed UHI influenced cooling loads relatively more than that of heating loads.

The factors influencing the UHI are complicated. In this study, the impact of land use types in different districts on UHI was the main aspect that had been considered. With regard to the various factors influencing the UHI and the UHI studies in Chongqing, more attention should be paid to and more researches need to be done in the long run.

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