Experimental study on community heat island intensity in hot-humid areas

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[Abstract] Mitigation of community heat island intensity (CHI) is important for developments of green building and eco-city. Previous studies conduct field measurements on CHI in hot-humid areas in both local and overall levels. The present paper conducted field measurements on air temperature of three communities in Guangzhou in summer sunny days, and studied the characteristic and mechanism of air temperature and heat island intensity in the levels of district, community and point. The results show that it is not reasonable to define CHI based on suburban meteorological station due to the significant impact of local urban heat island, and CHI should be defined based on nearby district meteorological station to avoid that impact. The point heat island intensity (PHI) is determined solely by the difference in design factors between point and community. The main design factors that influence CHI and PHI are solar shading area ratio, sky view factor and leaf area factor. Heat island intensity should be defined as the air temperature differences between the spaces in the same or adjacent scales.

[Keyword] Heat island intensity, community, district, hot-humid area, space scale

1. Introduction

This paper has a research objective as follows: 1) based on site tests of communities in hot-humid areas of China, to further understand the mechanism and changing rule of air temperature and heat island intensity of community; 2) to clarify the associations between the heat island intensities of community and its relative areas; 3) to provide scientific foundations for the prediction and design of heat island intensity of community in hot-humid areas.

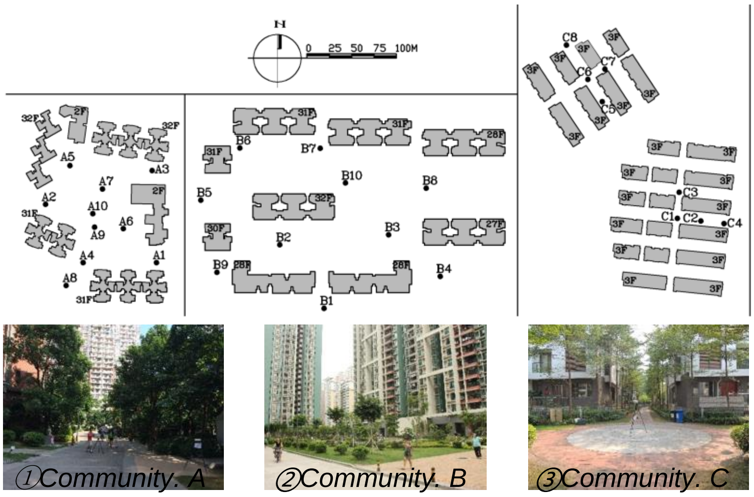

Fig. 1 Tested Community

2. Experimental methods

Three communities in Guangzhou, a typical city in hot-humid areas of China, were selected to be studied. See Fig.1&2 and Tab.1 for the details of the tested communities. The measuring points were determined with considerations of the variations of following factors (Fig. 1): a. underlying surface; b. architectural form and outdoor sunshade; c. frequency of use and area. The measurement was carried out in hot sunny summer in Guangzhou for 24 consecutive hours. Despite the different start and end time of all tests, the test data were presented and analyzed in the same time sequence of 19:00 - 18:00 of next day.

Table 1 Indicators of Community and the Time of Field Tests

Community	Layout	Floors (F)	Total Floor Area (M^2)	Green Area Ratio (%)	Building Density (%)	Floor Area Ratio	Measuring Time (2013)
A	Semi-Enclosed	31	225,000	55.9	20.4	4.99	18:00 Aug. 4th ~19:00 Aug. 5th
B	Staggered	30	356,000	35.0	25.0	4.64	8:00 Aug. 6th ~ 8:00 Aug. 7th
C	Regular	3	15,000	31.1	48.4	1.45	18:00 Oct. 3rd ~19:00 Oct. 4th

Based on previous studies, three indicators, shading area ratio (SAR), sky view factor (SVF) and leaf area index (LAI), were selected as the major design factors affecting the air temperature of community. SAR and SVF characterize the shading effect of buildings and trees. LAI is closely related to the cooling effect of trees, and a higher LAI means a larger evapotranspiration area of trees and a stronger cooling effect by trees. SAR is calculated as follows:

$$SAR = I_{dir}/I_{dir-NSO} \qquad ①$$

Where I_{dir} is the cumulative amount of direct solar radiation at a measuring point throughout a day, MJ/m^2, and $I_{dir-NSO}$ is the cumulative amount of direct solar radiation at a measuring point throughout a day in the absence of any shade, MJ/m^2. Different from the simple averaging shadow ratios at different moments, Equation ① defines

SAR from the perspective of energy instead of light, and the definition is more reasonable to study air temperature and heat island intensity.

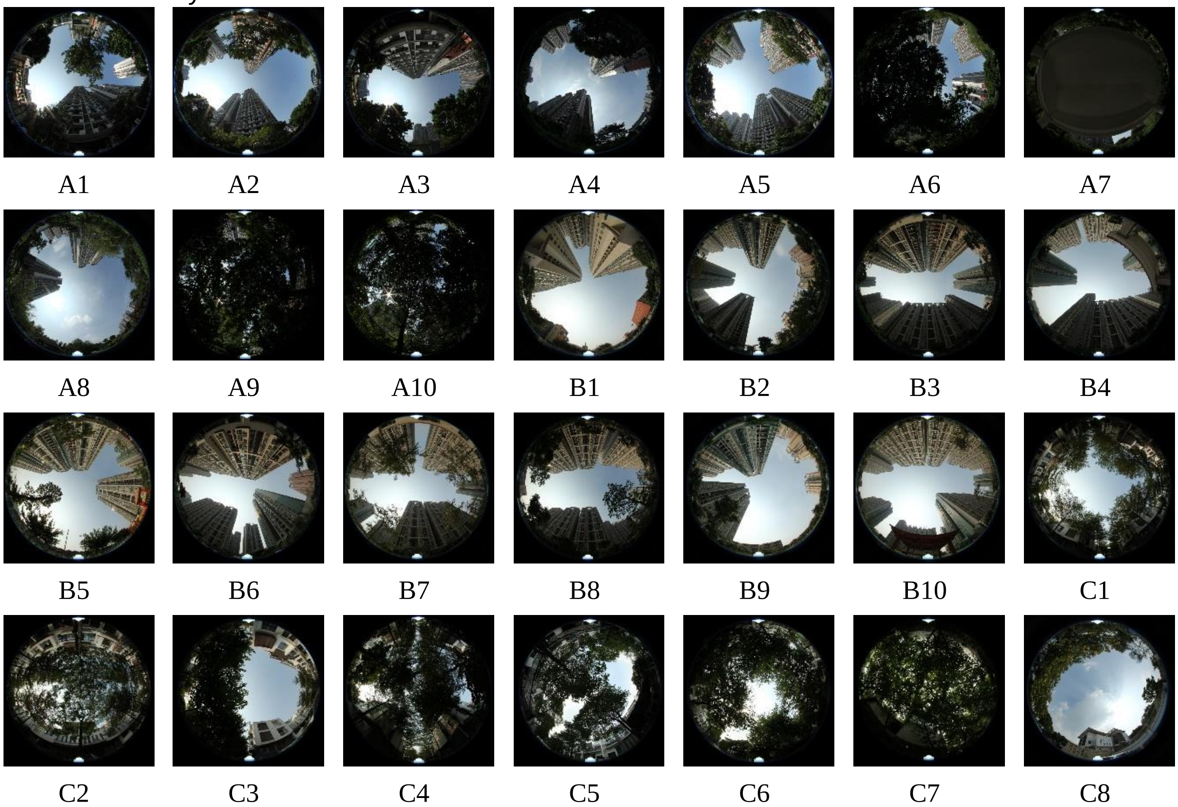

Fig. 2 Fisheye Photos of Site Conditions at Measuring Point

3. Results

In the following analysis, daytime is from 8:00 to 18:00 and nighttime is from 19:00 to 7:00 of next day. The hourly mean air temperature, such as 8:00, is the arithmetic average of air temperatures from 8:00 to 8:59.

3.1 Weather Conditions

All the three communities were measured in sunny and hot days. Guangzhou Suburb Weather Station (hereinafter referred to as the suburb station) is located in Luogang District, and the horizontal solar irradiance recorded at the test time was used for analysis. In the three community, the maximum daytime solar irradiance was 750 W/m^2 and above, the cumulative amount of solar radiation in the whole day was 18 MJ/m^2 and above, and the ratio between direct and scattered irradiance was 0.77-2.37. Community A had the strongest solar radiation among the three communities on their test day.

There are weather stations in the urban areas where the three communities are located. The urban districts where Community A is located is referred to as District A. In the three districts, the wind speed was high during the daytime and low at night, District B and C had higher wind speed with daily mean of 0.9 m/s, while District A had lower wind speed with daily mean of 0.3 m/s.

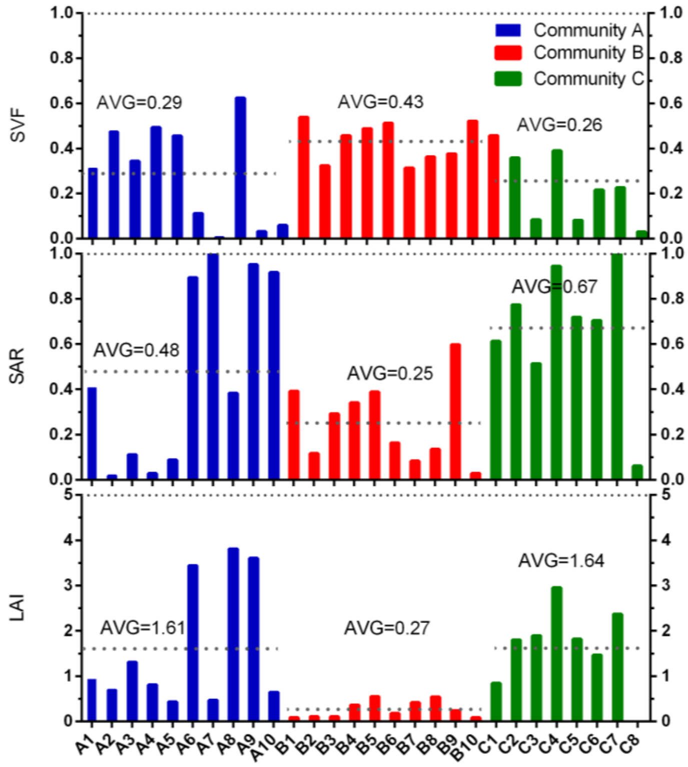

Fig. 3 Design Factor of Measuring Point and Community

3.2 Design factors

See Fig.3 for the design factor of each measuring point and community. The design factor of the community is the arithmetic average of those of its measuring points. Large variations in SVF, SAR and LAI of measuring points were found in Community A and C, indicating that the outdoor design of the communities has diverse features. The variation within community was small for Community B, showing that the outdoor design is relatively simple.

Community A has tall buildings and thick trees, and its SVF, SAR and LAI were 0.29, 0.48 and 1.61. Community B has staggered buildings, wider building intervals and low ratio of vegetation, and its SVF, SAR and LAI were 0.43, 0.25 and 0.27. Community C has regular buildings and high building density and ratio of vegetation, and its SVF, SAR and LAI were 0.26, 0.67 and 1.64. Based on the above analysis of design factors, it can be inferred that, under the same weather conditions, the air temperature will be lowest for Community C and highest for Community B at daytime. Nocturnal temperature, due to the combined effect of nighttime heat emission and daytime heat storage, has a more complex situation.

3.3 District heat island intensity (DHI)

The changes in temperature of urban and suburb weather stations during the tests are shown in Fig.4. It can be seen from the temperature of the suburb station that the weather is hot for tests of Community A and B, while is relative cool for Community C. The comparison between urban and suburb temperatures shows significant differences. The district air temperature, as a local thermal condition, has a more direct and significant impact on the tested community than the suburb air temperature.

The daytime, nocturnal and whole day DHI are shown in Tab.2. District A and C have positive daytime and nighttime heat island, and the intensity is higher at night. District B only has a certain degree of heat island intensity at night. The order of daytime DHI is A>C>B and is C>A>B for nocturnal DHI. As can be seen from Tab.2, development and population might be the possible causes of the difference of DHI. The greater the district development and population are, the higher the DHI. District C has higher nighttime heat island intensity than District A, which probably because of its dense anthropogenic heat.

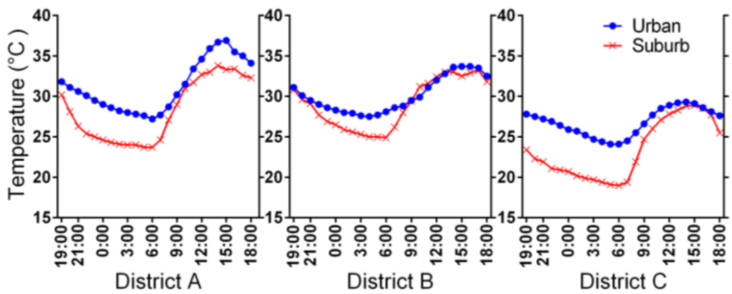

Fig. 4 Urban and Suburb Weather Station

Table 2 Heat Island Intensity of District (°C)

District	Daytime	Nocturnal	Day	2012 GDP* (Billion Yuan)	2012 Population* (x1,0000)
A	2.1	3.8	3.0	2121.48	117.12
B	0.2	1.8	1.1	745.65	71.2
C	1.2	5.2	3.4	1369.42	101.54

*: sources of data: http://www.gzstats.gov.cn/tjgb/qxtjgb/

3.4 Community heat island intensity (CHI)

Since the measuring points covered a variety of environmental conditions in the communities, the air temperature of the community was calculated as the average of all its measuring points. See Fig.5 shows the time change of air temperature for the three communities. The CHI was according obtained in Tab.3, which were based on urban and suburb weather stations respectively.

As can be seen from Tab.3, the daytime CHI based on urban weather station is in order of B>C>A, which is different with the order analyzed by design factors B>A>C. The inference from design factors should satisfy the premise of the same weather conditions. It can be known that Community A had significantly stronger solar radiation than C on the test day. Thus it can be reasonably inferred that under the condition of intense solar radiation, the cooling effect of solar shading becomes more significant, resulting in a greater cool island intensity of Community A than Community C.

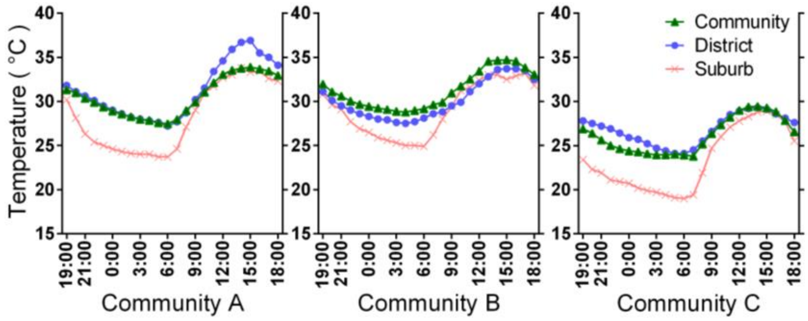

Fig. 5 Community Temperature

Table 3 Heat Island Intensity of Community (°C)

Community	Urban Weather Station			Suburb Weather Station		
	Daytime	Nocturnal	Day	Daytime	Nocturnal	Day
A	-1.5	-0.1	-0.7	0.6	3.7	2.3
B	1.2	1.1	1.1	1.4	2.9	2.2
C	-0.1	-1.0	-0.6	1.1	4.2	2.8

The daytime CHI of Communities A and C are negative when based on urban weather station, and become positive when based on suburb weather station. Different calculation leads to opposite results of CHI due to the impact of district heat island, and this impact is more obvious at night. Interference of DHI can also cause changes in the sequence of CHI. As known from the previous analysis, Community B has large SVF, small SAR and small

LAI, resulting in poor thermal environmental design and high heat island intensity. The same result was obtained while based on urban weather station. The DHI of District B is lower than A and C. When based on suburb weather station, the nocturnal and whole day CHI of Community B become the lowest, which is caused by DHI of District B and obviously inconsistent with the actual situations of the community.

It can be therefore indicated that the CHI calculated on the basis of suburban weather station, due to the impact of district heat island intensity, can not be used to reasonably evaluate the real performances of thermal environment design of communities. It can also be indicated that the interference of district heat island can be removed and the evaluation can be more reasonable while defining CHI on the basis of urban weather station.

3.5 Point heat island intensity (PHI)

Fig.6 shows the daytime, nighttime and whole day air temperatures of measuring points. Here Community A is taken as an example to analyze the relationship between daytime air temperature and design factors of the measuring point. Measuring points of A3, A2 and A8 have higher air temperatures, and A9 and A10 have lower air temperatures. It can be seen from Fig.2 that A3, A2 and A8 have lower SAR and higher SVF, which take more solar radiations into ground and produce larger daytime temperature rises. On the other side, the points of A9 and A10 have higher LAI, lower SVF and larger SAR, which take less solar radiations into ground and produce smaller daytime temperature rises.

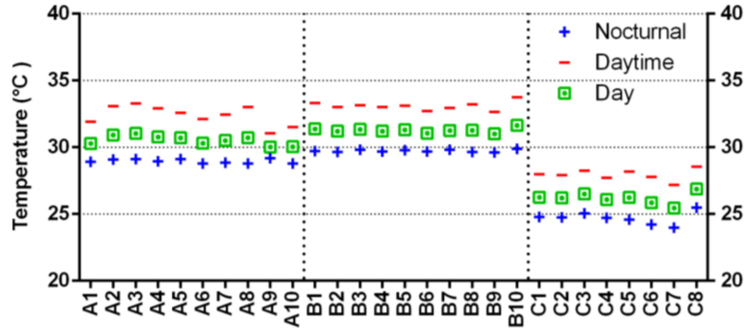

Fig. 6 Measuring Point Air Temperature

The nighttime air temperatures are different from the daytime, and all measuring points in the same community are almost the same in air temperatures. This makes the whole day air temperatures change closely with the daytime air temperatures. To sum up, the daytime and whole day air temperatures and the difference of daytime and nighttime temperatures of measuring point are closely related to its design factors. Greater SVF, lower SAR and lower LAI would produce a higher daytime and whole day air temperature, and greater SVF would produce a larger daytime and nighttime temperature difference.

In order to understand the change of temperature at measuring points and quickly determine the distribution of air temperature in community, the point heat island intensity (PHI) was defined in this paper as the air temperature difference between point and community. See Fig.7 for the calculated daytime, nighttime and whole day PHI.

It is reasonable to make the hypothesis that the PHI is related to the difference in design factors between point and community. To verify this hypothesis, the design factors difference for each measuring point was calculated, and a regression relationship was built between the PHI and the difference as follows:

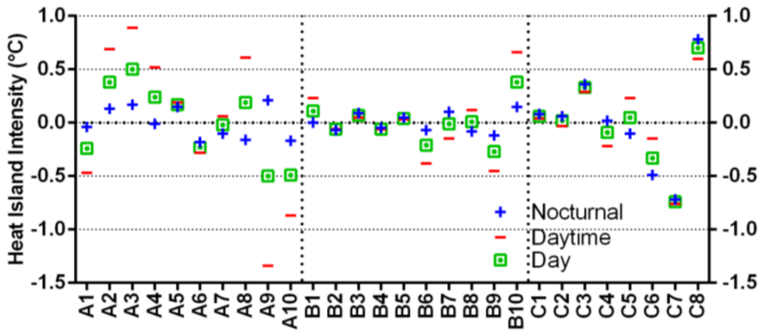

Fig. 7 Heat Island Intensity of Measuring Point

$$PHI_d = -1.23\Delta SAR \quad (R^2=0.524) \qquad ②$$

$$PHI_n = -0.448\Delta SAR \quad (R^2=0.244) \qquad ③$$

$$PHI = 0.602\Delta SVF - 0.541\Delta SAR \quad (R^2=0.618) \qquad ④$$

Where PHI_d, PHI_n and PHI are the daytime, nighttime and whole day PHI, ΔSAR is SAR difference of point, and ΔSVF is SVF difference of point.

It can be known from the equations that, the daytime PHI is negatively correlated to SAR difference, the whole day PHI is associated with SAR and SVF differences, and the nighttime PHI shows no significant relationship with design factors. The values of constant terms in the regression equations are not significant and close to 0, which well verifies the proposed hypothesis.

3.6 Spatial scales

According to the above study, the spatial scales related to community were summarized in Fig.8. Suburb and urban areas compose a region, the district is part of the urban, the community is part of the district, and the measuring point is part of the community. The scale in a descending order is region→urban (suburb)→district→

community→measuring point.

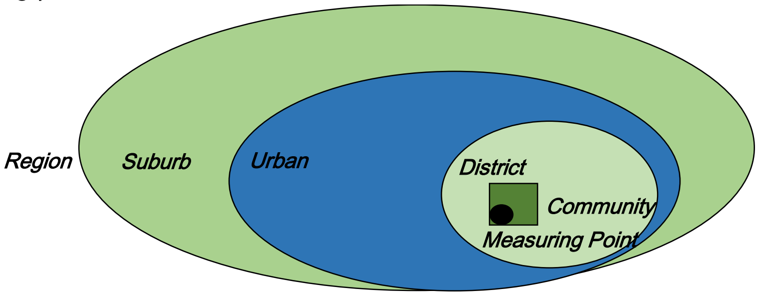

Fig. 8 the Space Scale Related to Community

From the perspective of climate, it can be known that the region, affected by the larger scale of topography and atmospheric circulation, forms certain local climate. Urban and suburb climates are formed in the context of regional climate, and their difference is mainly related to their thermophysical properties on underlying surface and anthropogenic heat. Microclimate of each urban district is in the context of urban climate and affected by its own development intensity and underlying construction. Microclimate of community is in the context of that of district and influenced by its thermal environmental design. Microclimate of measuring point is in the context of that of community and influenced by its design factors. In summary, there is a close physical relation between the climates in the same or adjacent spatial scales, and the climate of the upper level scale acts as a background affecting the climate of the lower level scale.

The above analysis helps to further clarify the results of this study. The temperature difference between urban and suburban areas (DHI) was studied first. They are in the same level of spatial scale, and the difference between urban and suburb air temperatures can better characterize the features of thermal environmental designs of city. When the concept of urban heat island intensity was brought into community, cross-level cases appeared, and the scale of district was skipped. Between the two cross-level scales, there is no direct relation in their climates and air temperatures. Therefore, the CHI based on suburb weather station can not be used to evaluate the design of community. Community is adjacent to district in spatial scale, and thus the CHI defined based on urban weather station is more reasonable. The same indications can be obtained for the PHI.

4. Conclusions

Based on the site tests of air temperature and heat island intensity of three communities in the hot-humid region of China, the following conclusions are drawn:

1. The greater the district development and population are, the higher the daily district heat island intensity. Nighttime heat island intensity was higher than daytime in district.

2. The community heat island intensity calculated on the basis of suburban weather station, due to the impact of district heat island intensity, can not be used to reasonably evaluate the real performances of thermal environment design of communities. The interference of district heat island can be removed and the evaluation can be more reasonable while defining community heat island intensity on the basis of urban weather station.

3. The heat island intensity of community is determined by its thermal environmental designs and background weather conditions. Greater SVF, lower SAR and lower LAI would produce a higher daytime and whole day air temperature, and greater SVF would produce a larger daytime and nighttime temperature difference. The effect on heat island intensity by solar shading would become more significant under the condition of intense solar radiation.

4. Defined as the temperature difference between point and community, the point heat island intensity is related to the design factor difference between point and community. The daytime point heat island intensity is negatively correlated to SAR difference, and the whole day point heat island intensity is correlated to SAR difference positively and SVF difference negatively.

5. The spatial scale associated with community in a descending order is region→urban (suburb)→district→community→measuring point. There is a close physical relation between the climates in the same or adjacent spatial scales, and the definition of heat island intensity should take the temperature difference between the space in the same or adjacent scales.

The definition of community heat island intensity in the present paper can be used for designs and evaluations of green buildings and eco communities. The definition and equations for point heat island intensity as well as the test method of design factors can be used to guide the measurements of heat island.

Acknowledgment

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