Urban planning elements affect thermal environment from solar radiation in subtropics

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Abstract

Urban planning elements are crucial factors affecting the absorption and storage of heat from solar radiation in ground surfaces. This study examined the influence of heat storage capacity and urban planning methods on environmental hotspots.

We examined the campus of National Taipei University of Technology (NTUT), including urban planning elements such as the building structures, road pavement materials, water bodies, and vegetation. The study was divided into measurement and simulation.

The study results indicate that: The thermal properties of urban planning elements exert significant influence on the heat storage of urban sites. The arrangement of building clusters and the mutual exchange of energy among them causes stagnant wind fields and heat storage. The evapotranspiration from water bodies and grass creates high moist enthalpy, which is difficult to dissipate.

Keywords: heat storage capacity, environmental hotspot, computational fluid dynamics, urban planning element, urban heat storage

1. Introduction

Urbanization has caused natural surfaces to be replaced by human-made materials, thereby increasing anthropogenic waste heat and energy consumption, altering ambient radiant heat, air humidity, and atmospheric fluids, and affecting microclimates at the mesoscale [1]. Most of the land cover in urban areas are impervious artificial surfaces, which upset the balance of energy in the Earth's surface [2,3,4]. During the day, urban surfaces absorb radiant heat from the sun and then slowly release the heat that they have accumulated after sunset, affecting the local microclimate [5,6]. The cement and concrete in buildings and the asphalt mixtures in road pavement all have high solar heat absorption and storage capacities [7,8], which allows them to store large amounts of heat during the day and then release it back into the atmosphere during the night [6,9,10]. Climate change and the reduction of rising ambient temperatures are major climate issues in many countries.

Rough surfaces are the main factor of urban heat storage, so urban planning and design must take into consideration changes in ambient energy as well as the influence of the heat properties and capacity of pavement material. A wide variety of design methods and strategies must be employed to cope with climate changes. Most past studies focused on analyzing and comparing various surface materials or investigated the influence of surface temperatures on ambient heat flux. Little research has been conducted into the influence of surface heat properties on the heat budget of urban environments and the key factors of heat storage.

This study examined the influence of urban planning elements on the ambient heat storage of specific sites. We measured physical factors of a campus environment at the site scale, input the measurements

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into

ArcGIS for a preliminary overlay analysis, and then employed computational fluid dynamics (CFD) software for comprehensive simulation of the campus environment. This model increases understanding of the heat budget of the site, thereby enabling identification of the key factors influencing the heat storage of surfaces and the air in hot and humid urban environments.

2. Theories and Methodology

We chose National Taipei University of Technology (NTUT) during summer as the site of this study. The campus of NTUT comprises varying urban planning elements and has the diversity of a small city. We therefore chose it as our simulation target and applied the typical meteorological year 3 (TMY3) of Taipei to our simulations. The measurements obtained from the site were used for heat storage calculations and converted into background conditions and the data needed for CFD simulations. Integration of simulation software and measurement data increased the accuracy of the simulation results

2.1. Theories associated with urban thermal environments

Urban climates are the climate characteristics that differ from surrounding natural areas due to urban development. Urbanization alters heat balance and changes the regional climate to an urban climate. The heights and shapes of building structures, the directions of streets and buildings, and the properties of surface materials in urban areas all exert a certain degree of influence on urban climate. This study investigated the mutual influence and connections between urban climate conditions, namely, solar radiation and fluid wind field, and surrounding urban planning elements.

• Urban energy transfer

The balance of energy between the atmosphere and urban environments. Influencing factors include shortwave radiation from the sun, longwave radiation reflected off rough surfaces, thermal energy released by different ground surfaces, the sensible heat exchanged between fluids and the ground, evapotranspiration heat from plants or the ground, and anthropogenic heat. Oke [1] developed an equation of energy balance between the air and ground structures in urban environments:

$$Q^* + QF = QH + QE + \Delta QS + \Delta QA \tag{1}$$

Q*: net radiant flux, which is the shortwave and longwave radiation absorbed by urban ground surfaces

QF: anthropogenic heat flux

QH: sensible heat flux

QE: latent heat flux

 ΔQS : heat stored by ground surfaces, buildings, and aboveground objects

 ΔQA : convection heat

This study mainly examines the heat stored by ground surfaces, buildings, and aboveground objects (ΔQS) and includes other influencing factors of ambient energy for reference and discussion. As our scope is limited to the thermal energy reactions generated by urban planning elements, we did not conduct an in-depth discussion of anthropogenic heat

Solar radiation

Givon [11] pointed out that the amounts of solar radiation received by urban and suburban areas are basically the same, but the longwave radiation released by the ground and the dense buildings in urban areas are absorbed and reflected numerous times by surrounding surfaces, which results in significant differences between urban and suburban areas in longwave radiation near the ground surface. Urban ground surfaces exchange heat with the air near the ground surface by reflecting shortwave solar radiation and engage in convective heat transfer by releasing longwave radiation.

• Urban wind field

The roughness of different urban areas impacts ground surface resistance, airflow scale and intensity, and wind speed conditions within the site environment [12]. When air flows through areas with rough

surfaces, the roughness influences the boundary layer of the ground surface, which in turn changes the average speed, pressure, and thickness of winds and impacts the turbulent flow field. The influence of ground surface roughness on the wind field generates different gradient wind speeds in different areas.

• Evapotranspiration

Evapotranspiration is an important factor of microclimate balance and is closely related to climate background conditions, soil water content, ground surface vegetation, and plant species and characteristics.

We referred to the Penman-Monteith equation to estimate the evapotranspiration from water bodies and vegetation:

$$EA_{PM} = \frac{0.408(Rn - G) + r\frac{900}{T + 273}u^2(e_s - e_a)}{\Delta + r(1 + 0.34u_2)}$$
(2)

where

EA: evapotranspiration [mm/day]

 $\Delta\!\!:$ the slope of the vapor pressure curve [kpa/°C]

Rn: net radiation [MJ /m2 /day]

G: soil heat flux [MJ /m2 /day]

r: psychrometric constant [kpa/°C]

u2: wind speed measured at height of 2 m [m/sec]

(es - ea): difference between saturated vapor pressure and actual vapor pressure [kpa]

2.2. Thermal properties of urban planning elements

The thermal properties of urban planning elements have significant influence on the thermal properties of pavement materials and building environments. The primary factors of their heat storage capacity include the thermal conductivity coefficient (k), density (ρ), and specific heat (c). These thermal properties are fixed values within substances. The thermal conductivity coefficient (k) indicates the capacity of a material to conduct or transmit heat and influences heat conduction speeds at high and low temperatures (Table 1). Pavement materials with low thermal conductivity will be heated at the surface, while those with high thermal c1nductivity coefficient of pavement surfaces can lower the heat flux of pavements under solar radiation and at high air temperatures, which will lower road surface temperatures and temperatures near the ground surface. Specific heat (C), also known as specific heat capacity, is the amount of energy that a unit mass of a substance requires to rise 1 °C in temperature. Depending on the circumstances, C can be further divided into specific heat capacity at constant volume (cv), and specific heat capacity at saturation with unit kJ/kg·K. In contrast, thermal resistance (R) refers to the capacity of a substance to resist the transmission of heat and is the reciprocal of k.

Table 1.	Thermal	properties	of surface	materials

Surface materials	Black non-metal surfaces, asphalt	Common concrete, aggregate concrete	Brick, stone, wood, etc.	Grass, clay mixed with grass, bare soil
Thermal conductivity				
coefficient k	1.05	1.51	0.81	0.76
[W/(m.K)]				
Density ρ [kg/m ³]	2100	2300	1800	1600
Specific heat capacity C [J/(kg.K)]	1680	920	1050	1010
Absorption rate a	0.90	0.7.	0.60-0.80	0.50
Thermal resistance R [m*k/ W]	0.95	-	1.08	1.32

2.3. Types of urban planning elements

Urban planning elements are crucial factors of urban climate. Complex and diverse structure surfaces can form different microclimate characteristics in an environment and exert a major impact on humans [14]. The thermal properties of surface materials, the shapes and configurations of buildings, and the distances between roads and buildings in urban environments all influence buildings, asphalt roads, brick pavements in plazas, vegetation, and park plazas and change the local microclimate. Guan [15] examined the thermal properties of surface materials and the influence of the ambient temperatures surrounding asphalt, concrete, brick, and grassy surfaces on microclimate. Assessing the influence of various surface materials on the microclimate of near-ground environments, Qin [3] derived that the interactions among road structures, material properties, and environmental factors are crucial to understanding the influence of urban ground surfaces on the heat island effect.

Xi [16] observed that urban planning elements can create different outdoor thermal environments and that common elements on campuses, such as building structures, plaza spaces, grass, soil, and vegetation, can be used to design subtropical urban environments. This study examined the most representative planning elements in urban areas, including building structures, asphalt roads, brick pavements in plazas, natural grass and soil, trees and vegetation, and water bodies.

3. Experiment Environment and Simulation Model

The NTUT campus in Da'an District of Taipei City, which covers 14.78 ha, served as the study area. The campus contains concrete buildings, asphalt roads and pavement, plazas and paths paved with bricks, pervious green spaces with vegetation, a small ecological pool, and a waterscape connected to a water course that runs outside the campus. With these various urban space elements, the campus environment resembles a miniature city.

3.1. Contents and background of experiment measurements

For the background of this experiment, we chose two different sets of weather conditions common during summer. We measured solar irradiance and cloud cover over four time periods between 9:00 and 17:00 on June 5, which was a cloudy day, and on June 25,2017, which was a sunny day. We chose three measurement locations with a high degree of pedestrian and vehicle traffic and one on building rooftop: A, B, C, and D. These locations included various surface textures, such as grass, brick pavement, concrete, and asphalt, which are the most representative material surfaces in urban environments (Fig 1).



Fig. 1. Locations of measurement point

We used the following instruments to collect data. For global solar irradiance, we used the LP PYRA 03 pyranometer. To measure air temperature and humidity at different elevations, we used an HOBO temperature relative humidity data logger. Comprehensive heat indexes air temperature TA, globe temperature TG, and relative humidity RH were measured using a handheld wet bulb globe thermometer. Heat flux sensors were used to measure the heat flux of surface materials. We used thermocouple wires to measure surface temperatures and then used CR1000 and CR800 to monitor and record data, as shown in Table 2.

Table 2. Parameters of experimental instruments

Measurement parameter/unit	Instrument	Measurement time	
Solar irradiance/ W/m ²	LP PYRA 03 pyranometer	9:00-11:00,	
Air temperature relative		11:00-13:00	
humidity / 90/04	HOBO UX100 Temp	13:00-15:00	
Air temperature $TA/9C$		15:00-17:00	
All temperature TA/ C	Handheld wet bulb globe	Measurements taken	
Radiation temperature 10/ C	thermometer AZ8778	for 10 minutes at	
Relative number of Why %		each location, 1 item	
Surface heat flux/ $^{\circ}$ C	Heat flux sensor	of data per minute;	
Surface temperature/ \mathcal{C}	Thermocouple wire	the mean of the	
Surface temperature, C	memocoupie wite	resulting 10 data	
Data loggers	CR1000 and CR800	items was calculated	
Dutu 1055015	CITIO00 and CIX000	for each location	

3.2. Settings of numerical model

We constructed a model of the campus using Rhino and then used computational fluid dynamics (CFD) software to simulate and analyze steady-state wind field characteristics under extreme weather conditions in the summer.

For the environmental parameter settings, we used the hot and humid summer environment in northern Taiwan for our background values and referred to the values of June 25, 2017 from the Taipei City weather station for our parameter settings. The actual measurements served as the input values for solar irradiance, temperature, humidity, and heat flux. The time intervals were calculated in hours, so there were 24 intervals in a day. Assuming that heat conduction remained constant during the selected time periods, the mean water-vapor flux and latent heat of evaporation of each time period were calculated, with the environmental measurements taken at 12:00 noon as the input parameters of the CFD simulations. The wind field settings were based on the mean wind speed on that day as shown by the weather station. Turbulent flow conditions were considered in the wind field analysis in the simulation model and calculated using a standard k- ϵ model.

4. Measurement Results on Site

With a subtropical summer climate as the background, we utilized mobile measurement in the campus experiment from 9:00 to 17:00 and obtained two sets of data, one from a sunny day and the other from a cloudy day. This enabled us to examine the influence of various urban planning elements on the heat budget of the site and understand their relationships with their surrounding environments. We used solar irradiance, surface heat flux and temperature, and relative temperature and humidity to conduct a preliminary comparison of the influences of the urban planning elements on the thermal environment of the site.

4.1. Influence of urban planning elements on physical parameters of environment

Based on our results, we can derive the thermal behavior of various road surface materials and their influence on the heat in the surrounding environment. We arrived at the following conclusions: As the measured data show, the temperatures for these 2days are similar, yet the surface temperatures of the sunny day (25, Jun.) are clearly higher than those of cloudy day (05, Jun.).

Among the thermal properties of the materials, thermal resistance R, thermal conductivity coefficient K, heat storage coefficient S, and heat storage capacity impact the surrounding air temperature and thermal energy release of road surface materials. Asphalt has high thermal conductivity, which causes it to store large amounts of heat during the day and release large amounts of heat during the night. It is thus one of the primary factors degrading thermal comfort in surrounding environments. Improvements can be made with regard to the heat storage capacity of asphalt concrete road surfaces through adjustment of the thermal conductivity coefficient and specific heat capacity of the material.

During some time periods, the surface temperatures of brick pavement may be close to or higher than

those of asphalt concrete because the thermal inertia and heat storage coefficient of brick pavement are second only to those of asphalt and because brick pavement also accumulates heat. However, brick pavement has a lower absorption rate and slower evapotranspiration, so the temperatures of air above brick pavement are lower than those above asphalt. As a result, brick pavement and grass can reduce the amount of heat above road surfaces and thereby improve the thermal environment of surrounding areas (Fig 2).



Fig. 2. Influence of urban planning elements on (a) temperature and (b) heat flux

Grass can absorb substantial amounts of heat but does not store all of it internally, which is beneficial to the lowering of temperatures. Although it is inevitable that urban environments will have more road surfaces, permeable or natural pavement materials are recommended so as to reduce the impact of road surfaces on urban climate. Such pavement materials conduct heat from the surface layer to the soil underneath, reduce surface temperatures as well as the amount of heat stored, and mitigate the influence of solar radiation on urban thermal environments.

Our psychrometric chart and enthalpy diagram reveals that the total enthalpy of asphalt concrete is higher than those of other road surface materials. Although grass presented lower temperatures, it exhibited the highest moist enthalpy value. This shows that a mutually influencing relationship exists between the enthalpy of surrounding air and the heat storage capacity of surface materials (Fig 3,4).



Fig. 3. Relationships between thermal properties and heat storage capacity of different materials and enthalpy of air in surrounding environment



Fig. 4. The thermal comfort of different surfaces in campus

5. Analysis and Discussion of Heat Storage in Site Simulations

We used measurement analysis and CFD simulation software to investigate the site environment further.

5.1. Influence of thermal properties of urban planning elements on physical environment and space

The studied site was divided in two zones i and ii. Zone i was planned mainly as grass, trees and pavement. Around noon the temperatures went down surround the trees. The cool air among tree canopies diffused outwards. The temperatures went up as the distance increased from the trees. Zone ii consists of planning elements besides the pavement, more important, of the buildings nearby, which had absorbed amounts of solar heat and appeared high temperature. For the building masses, wind fields were stagnated, the cool air among trees couldn't act the best results. (Fig 5,6)

The results of this study indicate a close relationship between heat and material type that generates environmental hotspots. These hotspots change depending on the weather; some move, others become worse, and still others display reduced capacity to store heat. This makes hotspots an unpredictable topic of research.

Finally, the study results indicate that greater building density will result in a greater heating effect, such that the cooling effect of trees and vegetation will be outweighed. Thus, in urban planning and design, the density of heat-accumulating bodies should be decreased so as to reduce the amount of heat accumulated between buildings. Green spaces should be designed to include good ventilation so that the cool air from the trees and vegetation can effectively regulate the microclimate.



Fig. 5. Relationship between urban planning elements and terrain (Zone i)



Fig. 6. Relationship between urban planning elements and terrain (Zone ii)

5.2. Influence of wind on heat storage in urban environments

Airflows can be found near the ground throughout urban environments, and the factors that influence the wind environment are varied and complex. Airflow has a wide scope of influence. In recent years, many researchers and organizations have examined the issue of using wind to improve urban environments. For instance, wind can enhance ground cooling efficiency, convective wind can diffuse exhaust fumes, and convection and heat exchange can alter effective air temperature and regulate climates and environments. Many issues involving urban waste heat or thermal comfort have been effectively improved. This study further discovered that while wind direction and speed may resolve existing environmental hotspots, they can also form new hotspots. The simulations show, that the increasing wind speed dose diffuse the heat in surroundings, that cuts down the temperatures in the microclimate (Fig 7).



Fig. 7. Influence of wind speed on heat storage in the environment at section A-B

5.3. Influence of evapotranspiration on physical environment and space

In the hot and humid conditions of subtropical urban environments, the evapotranspiration associated with parks and green spaces has a profound impact on thermal comfort. Areas with high moist enthalpy make people feel uncomfortable and also generate environmental hotspots unlike those caused by sensible heat (Fig 8).

The results of this study show that grassy surfaces fall within the uncomfortable zone (Fig 9). While the air temperatures above brick pavement were higher than those above grass, the air above brick pavement was less humid, thereby placing brick pavement closer to the comfort zone in the psychrometric chart, with a small portion within the comfort zone. Thus, in extreme weather conditions of high temperatures and high humidity, the air above grassy surfaces is actually less comfortable than that above brick pavement. We therefore recommend brick pavement in place of some of the grassy surfaces in areas with high humidity and no wind so as to prevent the sensible heat caused by evapotranspiration from creating environmental hotspots.



Fig. 8. Influence of evapotranspiration from water bodies and green spaces on heat storage of environment





5.4. Assessment of hotspot distribution in site environment

This study measured three influencing factors of heat storage to analyze and assess hotspots on campus.

Hotspot A is located in a space between two buildings. Because the space is very narrow, the airflow there is poor, which prevents the heat in the air from dissipating. The ambient temperature was thus around 38.5 °C.

Hotspot B is located in a corner between buildings, where there is a variety of plants and multiple layers of vegetation. Evapotranspiration releases moisture unto the air, and the area is in a wind shadow, so the heat cannot dissipate.

Hotspot C is surrounded by concrete building structures. When wind hits the surrounding structures, a wake forms on the leeward side. However, when too many wakes collide in the air, the airflows are blocked, which causes the wind to slow down. Added to the heat from the roofs, the temperature here increases to around 37.5 $^{\circ}$ C.

Hotspot D is located at the south entrance of the campus. The building on the east side means this location has almost no wind. Airflow takes away the heat from the roof, and because the art center is a three-story building, the wind sweeps downward and rebounds, returning the heat from the roof. The dual heating effects of the two buildings caused the location to become an environmental hotspot. In the afternoon as the direction of the sun changes, the temperature at the hotspot gradually drops (Fig. 10).



Fig. 10. Distribution of environmental hotspots on campus

6. Conclusion

In hot and humid climates, the thermal properties of urban planning elements have significant influence on the heat storage of urban environments. Hotspots form and change with irradiation duration and the wind field. These should be taken into consideration in the design of urban spaces.

Convection and heat exchange in wind fields can lower the overall temperature of an environment and reduce ground surface temperatures. They can mitigate the impact of road surfaces on the heat storage of surrounding areas both during the day and during the night.

In extreme weather conditions of high temperatures and high humidity, evapotranspiration from water bodies and grass creates high moist enthalpy, and it is difficult for the enthalpy in the air to dissipate. This means vegetation between closely-spaced buildings and green spaces with low wind speed are likely to become environmental hotspots.

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