SURVEYING THE THERMAL PROPERTIES OF AN URBAN HEAT ISLAND VERTICAL STRUCTURE INFLUENCED BY SUBTROPICAL SOLAR RADIATION

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Abstract - Man-made structures and paved surfaces in urbanized areas create a situation where heat from solar radiation does not readily dissipate and instead accumulates, causing the urban heat island effect. Much past research has investigated how features of the earth's surface play a role in the urban heat island effect, yet most of this research focuses only on the surface of the urban area. This study analyses collected data for climatic factors and visualized data of an urban vertical structure in order to explore the relationship between thermal energy distribution in a subtropical urban vertical environment and environmental factors. In order to understand the flow and location of thermal energy in an urban vertical environment and influencing factors, this study uses a remote-controlled drone Phantom 4 Pro to measure an urban thermal environment's vertical space structure. It then creates distribution figures for temperature, humidity, and enthalpy of an urban thermal environment's vertical structure. The research results indicate that parameter distribution for the two profiles of an urban vertical structure and the earth's surface properties are closely related. Apart from human influences, the main source for an urban heat island is an increase in thermal capacity. Vegetation can mitigate enthalpy of dry air yet is unable to effectively reduce enthalpy of moist air. Home to a subtropical climate with high humidity, Taiwan must consider issues related to latent heat, as the enthalpy of moist air impacts the comfort of those who live on the island. How much urban wind fields can mitigate an urban heat island depends on topography, the area's size, buildings, and vegetation. Heat in urban areas caused by a heat island can be driven out with ventilation from wind power and thermal buoyancy. Improved remote sensing technology has allowed us to garner more precise measurement data, and, in the future, we will be able to predict urban heat island heat distribution flow and influencing factors, which will be the basis for methods dealing with heat dissipation in an urban climate's vertical space.

Index Terms - Urban heat island, thermal capacity, enthalpy, temperature gradient, air convection

I. INTRODUCTION

Highlight a section that you want to designate with a certain style, and then select the appropriate name on the style menu. The style will adjust your fonts and line spacing. The loss of natural landscapes in addition to the creation of man-made structures and paved surfaces cause temperature increases in urban environments[1]. As a result, the surface's improved heat accumulation capabilities[2] result in the urban heat island effect and dust dome effect[3]. The urban heat island effect is a unique phenomenon of air temperature distribution, as the temperatures of the urban area are higher than those of the surrounding suburban areas[4],[5].The following factors cause an increase in the heat island effect: human-caused heat release, decreased plant cover, buildings being close together, reduced evaporation, widespread construction of asphalt roads during the urbanization process, and building materials that have high heat capacities due to their strong endothermic properties[6]-[9]. Buildings and roads are two major factors that cause high temperatures in urbanized areas [10], and covering the earth's surface with hard, man-made surfaces causes a 1℃ rise in temperature 25 meters above the ground[3]. In order to better understand the thermal behavior of the materials of surfaces in urban areas, many research articles investigate the relationship between air temperatures and the properties of materials that cover the earth's surface. The results have shown that vegetation lowers temperatures and that impermeable pavement increases surface temperatures [1],[11]. There are three main physics mechanisms and methods at play for how vegetation shapes the environment: (1) vegetation lowers wind speeds and increases turbulence, (2) vegetation weakens the effects of radiation, and (3) moisture evaporation from plants releases latent heat that influences thermal equilibrium [12]. Therefore, when exploring comfort levels, only by doing mapping for enthalpy energy can we explain thermal energy distribution in an urban microclimate [13]. Much past research has investigated how features of the earth's surface play a role in the urban heat island effect, yet most of this research focuses only on the surface of the urban area. Malaysian scholars discovered that microclimates are affected by different urban landscapes. The downtown area's temperature is higher and the humidity is lower, and green spaces have lower temperatures with high humidity levels. Areas with lakes have more open space, which is why wind speeds are higher, whereas areas with plenty of vegetation have lower wind speeds due to the close proximity of plants blocking the wind[14]. This study analyses collected data for climatic factors and data visualization of an urban vertical structure in order to explore the relationship between thermal energy distribution in a subtropical urban vertical environment and environmental factors.

Large scale meteorological surveys must be carried out in order to grasp the actual nature of urban heat island effect. Measurement methods are typically divided into the following categories: fixed surveying, satellite telemetry, and mobile surveying[15]-[18]. When measuring an urban heat island and the evolution of its structure, the influencing factors that most research in this field explore are wind fields, humidity levels, radiation temperature, and comfort levels[16],[19],[20]. There is little research on the vertical structure of urban heat islands though. This study incorporates mobile surveying concepts, and it uses a 4-axle remote-controlled drone Phantom 4 Pro to carry out measurements, survey the urban area in 3D, and survey its thermal properties. This allows us to obtain thermal energy distribution for two different profiles of an urban area. The purpose of this is providing data that can explain how thermal differences for varying surface properties as well as changes occurring in the environment.

II. RESEARCH METHODOLOGY

A. Scope of Research

The primary research method was on-site measurement, which took place at Wenshan District (121°33′E, 24°59 ′N; Fig. 1) in Taiwan's capital, Taipei City. In order to survey temperature and humidity distribution of an urban environment's vertical structure, two profiles of the urban area with different surface properties were chosen and then analyzed. Jingmei Riverside Park and its parking lot, which are located on the north side of Taipei Zoo, served as the measurement area (Fig. 2). The total length of these two profiles' land strips are A:240 meters and B:180 meters. Measurements were taken at the following elevations: 1.5m, 20m, 40m, 60m, 80m, 100m, and 120m. Profile A is an open area with water and a large parking lot with a tarmac surface, whereas Profile B is an open area with water and grass. These two large areas with different surfaces are very representative of the environmental characteristics for an urban area and suburban area.

A Phantom 4 Pro drone was used to carry out on-site measurement in order to survey temperature and humidity distribution of an urban environment's vertical structure. The drone went to Jingmei Riverside Park, located in Taipei's Wenshan District, to measure the thermal parameters of the urban environment's vertical structure. The purpose of doing this is to measure how two separate surface properties of an urban thermal environment affect the thermal environment's vertical structure differently.

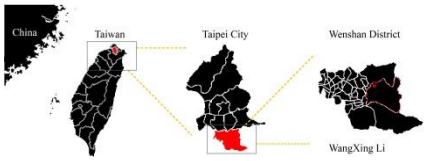


Figure 1. Research Scope MapMaps of Research Scope



Figure2. Measurement Profiles

B. Procedures for Creating Distribution Figures for Temperature, Humidity, and Enthalpy of the Urban Environment's Vertical Structure

Surveying for the distribution figures for temperature, humidity, and enthalpy of the urban environment's vertical structure included the following aspects: on-site measurements, use of instruments and mounts, route planning, collection of the environment's meteorological data, planning, and creating GIS data. Current research on urban heat islands is limited, as it only measures at the earth's surface. However, in order to understand temperature and humidity distribution of an urban thermal environment's vertical structure, this study utilizes a drone to carry out mesh-style measurements for the temperature and humidity of an urban environment's vertical structure. Furthermore, the enthalpy figures of the urban environment's vertical structure are obtained by calculating with a formula. Mesh survey methods are used to enter the measurements for the profiles' environmental parameters into the GIS. We then analyze the visualized GIS, allowing us to understand the relationship between the temperature of the urban environment's vertical structure and the distribution of energy. Following this we explore the links between a paved structure and its environmental factors.

1. Measurement of Thermal Environment and Data Collection

On-site measurement is the most direct method for surveying an urban area[19]. Therefore, this study uses data garnered from on-site measurement as its basis. Measurement took place on a sunny fall day in Taipei. The temperature and humidity of the two profiles' areas were measured from 1:05-1:12pm and 1:55-2:05pm on November 7, 2017 (Fig. 3).

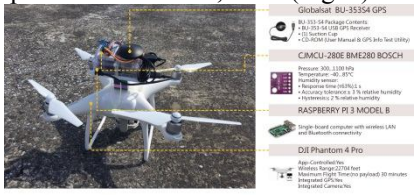


Figure3. Measurement Recording Device and Equipment are Attached to a 4-axle Drone

The plan for the flight assignment's elevation has tiers, and the drone flew 10km/h (Fig. 4). A Raspberry PI 3 Model B served as the recorder, and it recorded and collected the air temperature (Ta), humidity (RH),

atmospheric pressure, each elevation's atmospheric pressure, elevation, and coordinates every 0.2 seconds.



Figure 4 Illustration of Flight Path Plan

2. Formula for Calculating Enthalpy

This study uses the enthalpy of the total heat quantity in the air to explore the heat distribution of the urban environment's profiles. Enthalpy was obtained by the following equation:

$$h = C_p\theta + x(r + C_v\theta)$$

h=enthalpy (kJ/kg')

θ= air temperature (℃)

Cp=specific heat at constant pressure of dry air, 1.005 (kJ/kg·K)

Cv=specific heat at constant pressure of vapor , 1.846 (kJ/kg·K)

X=absolute humidity (kg/kg')

R=latent heat of vaporization at 0 °C, 2501.1 (kJ/kg)

III. ANALYSIS AND DISCUSSION

A. Environmental Monitoring Parameters

Fig. 5 shows the environment's average temperature, humidity, wind speed, and wind direction for this study's monitoring period. Only the environmental parameters during the time of measurement were used, and this took less than an hour. There were differences in temperature between Profiles A and B during the time of measurement. The average temperature of Profile A (31.9℃) was 2.4℃ lower than that of Profile B (34.3℃), and the difference in humidity was 5.8%. The average wind speed was within 2 m/s, and the wind blew in from the east.

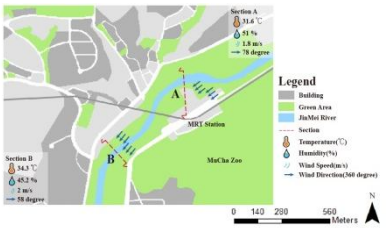


Figure 5. Environmental Data of Fixed Point Measurements

B. Data for Environmental Parameters of Profile A

1. Temperature

Fig. 6 shows visualized data of temperatures for Profile A taken during the measurement date, which lasted from sunrise to the measurement time. The surface became hotter because it absorbed solar radiation, and measurement data indicated that the hottest surface temperature for Profile A was 36℃. The temperature decreased as elevation increased; the average temperature at the surface (34.5℃) was 5℃ hotter than at 120 meters (29.5℃) above the ground. The surface is constantly absorbing heat during the daytime, causing the temperature of nearby air to increase. Then, convective heat transfer causes heat to rise, resulting in a type of distribution where the temperature decreases as the elevation increases. This is known as vertical temperature lapse rate.

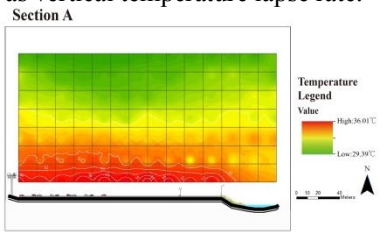


Figure6 Temperature Changes in Profile A's Vertical Measurements

2. Relative Humidity

Fig. 7 illustrates visualized data of the relative humidity for Profile A taken during the measurement date. The measurement data indicates that the relative humidity of Profile A increases as the elevation gets higher. The average humidity at 1.5 meters off the ground is 50.3% and 62.4% at 120 meters, which means the relative humidity has a difference of 12.1%. The most significant difference in relative humidity was between 2 meters (50.3%) and 20 meters (60.4%). However, the rate of increase for relative humidity tapers off as the elevation gets higher.

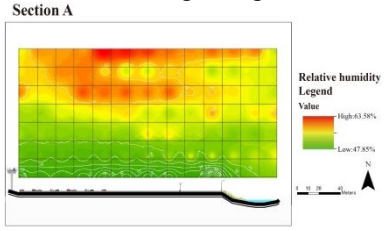


Figure7. Changes in Relative Humidity for Profile A's Vertical Measurements

3. Enthalpy

The total heat quantity is known as enthalpy, which is separated into sensible heat (enthalpy of dry air) and latent heat (enthalpy of moist air). The discussion on the enthalpy of dry and moist air below used a formula for calculating enthalpy.

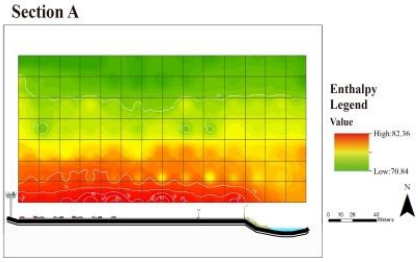


Figure8. Changes in Enthalpy for Profile A's Vertical Measurements

Fig. 8 indicates visualized data of enthalpy for Profile A taken during the measurement date. The measurement data shows enthalpy decreases as the elevation increases. The average enthalpy value is 8 kJ/kg' higher at the surface (79.3 kJ/kg') than at 120 meters (71.3 kJ/kg') above ground. The trends for enthalpy are similar to the temperatures of Profile A from the surface to 120 meters above ground.

Figures 9 and 10 indicate visualized data of the enthalpy of dry air and the enthalpy of moist air for Profile A taken during the measurement date.

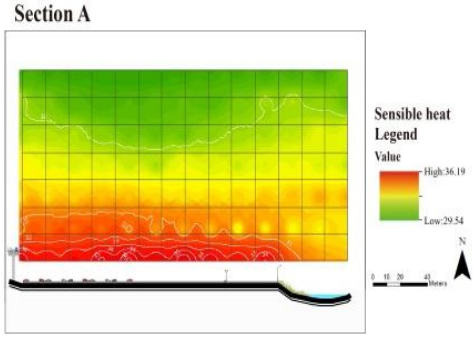


Figure9. Changes in Enthalpy of Dry Air for Profile A's Vertical Measurements

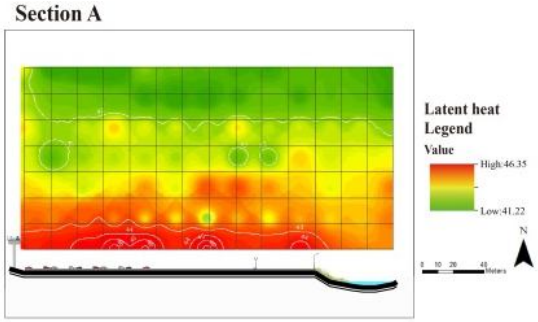


Figure10. Changes in Enthalpy of Moist Air for Profile A's Vertical Measurements

C. Data for Environmental Parameters of Profile B

1. Temperature

Fig. 11 shows visualized data of temperatures for Profile B taken during the measurement date.

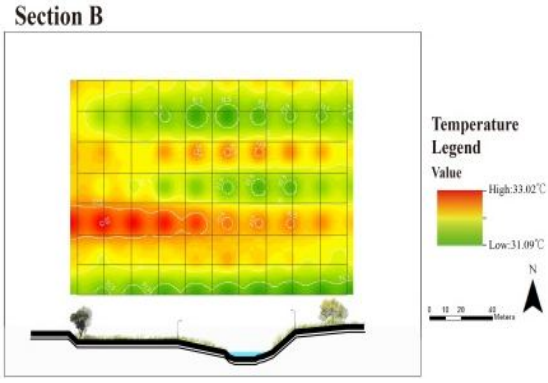


Figure11. Temperature Changes in Profile B's Vertical Measurements

2. Relative Humidity

Fig. 12 shows visualized data of the relative humidity for Profile B taken during the measurement date.

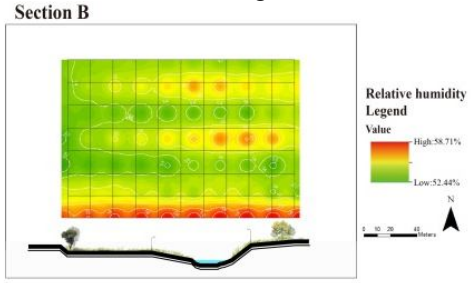


Fig 12Changes in Relative Humidity for Profile B's Vertical Measurements

3. Enthalpy

Fig. 13 indicates visualized data of enthalpy for Profile B taken during the measurement date.

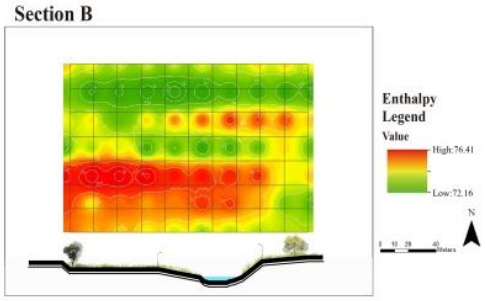


Fig 13Changes in Enthalpy for Profile B's Vertical Measurements

Figures 14 and 15 indicate visualized data of the enthalpy of dry air and the enthalpy of moist air for Profile B taken during the measurement date.

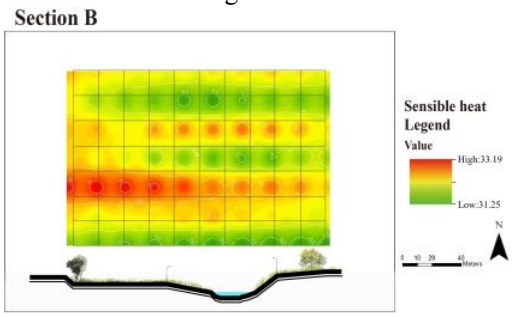


Fig 15Changes in Enthalpy of Dry Air for Profile B's Vertical Measurements

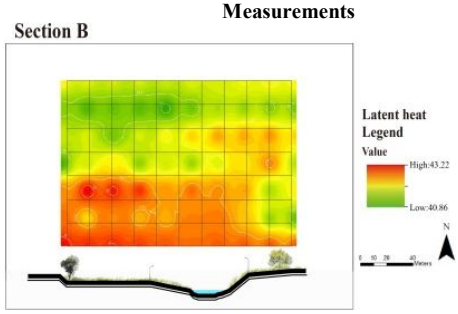


Fig 16Changes in Enthalpy of Moist Air for Profile B's Vertical Measurements

D. Summary

The figures showing the linear trends of Profiles A and B explain the trends for temperature, humidity, and enthalpy (Fig. 16). The data's results reveal the trends, which are Profile A's temperature is highest at the surface, and as the elevation increases the temperature decreases significantly. However, for Profile B the

trend is the opposite of this. Although there is little change between elevations, the temperature is lowest at the surface and the temperature slowly gets warmer as the elevation gets closer to the top, which has the highest temperature. Profile A's humidity increases as the elevation increases, and for Profile B relative humidity decreases as the elevation increases. As for enthalpy trends of Profiles A and B, both have high energy at the surface, and energy decreases as the elevation increases.

Profile B's temperature is higher than that of Profile A, and this is possibly due to interference from temperature differences because of the environment's location and environmental factors in the surrounding area. The area closest to the surface has turbulent flow, wind shear, and air flow, which are influenced by the earth's surface and artificial surfaces. Therefore, a complex heat exchange is thus present. As a result, Profile B's temperatures change due to elevation, and it may be like this because of turbulent flow from the wind field influencing the environmental parameters during the measurement time.

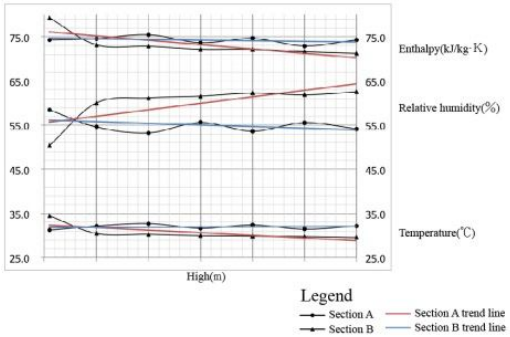


Fig16. Temperature, Humidity, and Enthalpy Trends of Profiles A and B

E. Overall Discussion

This study uses large surfaces of (1) tarmac and (2) grass, which represent the environmental characteristics of an urban area and suburban area, respectively. The study also explores the relationship between environmental characteristics and the environmental factors of a vertical structure in order to understand whether environmental characteristics influence the thermal energy flow of an urban vertical space. After comparing figures, influential differences were separated into three sections and then analysis was carried out, which can be seen below:

1. Solar radiation is the primary source of heat in a natural environment. Different surface materials have varying thermal properties and thermal energy storage capabilities. The primary influential factors for the surface materials of urban areas are thermal conductivity (k), density (ρ), and specific heat (c), and they cause minor differences in volume heat capacity and the surface's endothermic capabilities[12]. This study's team[22] explored the assessment of the total heat flux for the campus environment's surfaces, and it used the different thermal properties and thermal energy storage capabilities of varying surface materials along with thermal capacity concepts to explore how different surfaces influence an urban environment's heat budget. The data indicates that there is a large difference in surface temperature between the grass surface and tarmac surface. In fact, the surface temperature measurement results and this study's highest recorded temperature (at 1.5 meters) are the same. Results for thermal capacity calculation reveal that tarmac has a higher thermal capacity, as the thermal capacity of tarmac at noon was 8,328,760 (J/m3), which is about 30 times higher than that of grass at 258,560 (J/m3).

2. We took the concepts of heat into consideration, so we used enthalpy to discuss the total enthalpy value. Concerning the enthalpy of dry air, its value is representative of temperature, meaning the enthalpy value of dry air is the sensible heat value. As for the enthalpy of moist air, it is representative of the latent heat value. An urban heat island accumulates a great amount of heat, and temperature values are not able to sufficiently express the actual situation of thermal energy. Therefore, enthalpy is used to discuss the urban heat island's thermal energy. Fig. 17 indicates the trends for the enthalpy of dry air and moist air. The tarmac surface has a high value for the enthalpy of dry air, and a high temperature for enthalpy of dry air corresponds to temperature, so it quite simply has a high temperature. However, the tarmac's ability to have a high value for the enthalpy of moist air is a result of most the heat in thermal capacity emerging. Some of this has to do with once heat is released the enthalpy of dry air is increased, and at the same time thermal energy near the surface is converted into enthalpy of moist air due to water vapor. This can be seen in Profile A's high value for total enthalpy, and this situation makes the urban heat island effect more severe.

After the grass in Profile B absorbs the radiation, evaporation sends the heat away. It is quite notable that evapotranspiration lowers the surface temperature and the air temperature of the surrounding area. The enthalpy of dry air for the grass is much lower, causing the environment surrounding the surface to be cooler. However, the enthalpy of moist air is not lower, as a large amount of water vapor is converted into latent heat, which is shown in the high enthalpy of moist air for the area around the surface. Overall, the enthalpy of an urban heat island is heavily influenced in different ways by the surface, topography, and plants.

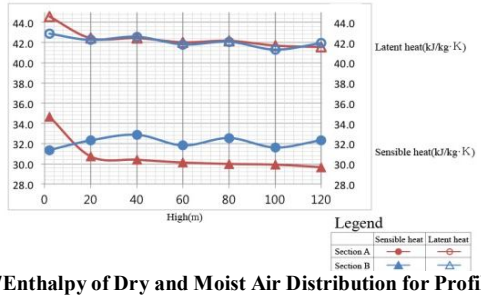


Fig 17Enthalpy of Dry and Moist Air Distribution for Profiles A and B

3. Convection occurs when a fluid moves and then transfers heat, and convection is caused by the earth's surface being hit by solar radiation, which heats the surface and the surrounding air. When the temperature rises, the air's volume expands and its density lowers, and because the density is different buoyancy causes the fluid to move in a vertical direction, as the heat is transferred upwards. The surface contains a great amount of heat, and at middle and high elevations the amount of heat lessens. Heat at a high altitude suddenly decreases and then after that changes very little between different elevations, which is how the thermal boundary layer is created.

The special aspect of the thermal boundary layer is significant changes within the layer itself. This occurs because the temperature boundary layer has a larger temperature gradient, and this causes the temperature boundary layer to be a major area for convective heat transfer. Fig. 18 shows the temperature gradients of Profiles A and B.

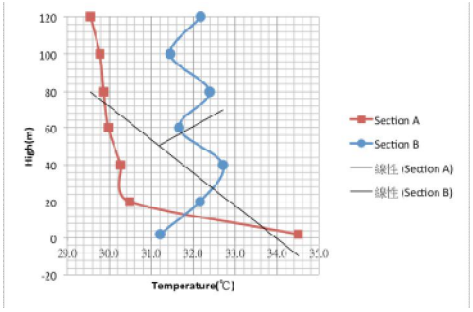


Fig18Temperature Gradients of Profiles A and B

In addition to the above information, apart from being influenced by materials, the thermal energy flow of the two profiles' urban structures is also affected by how much a horizontal wind field can make thermal energy flow. In Profile B, at 40 meters above the ground at the lane near the river embankment, measurements indicate a high temperature and a high heat content(please see Figures 11 and 13). The area next to the measurement location is a road, so the heat it provides is influenced by wind that blows horizontally above the measurement area. As a result, there is a high temperature and high heat content.

CONCLUSION

The survey results for two small strips of an urban area that is an urban heat island vertical structure are able to reflect how two different representative environmental characteristics have different thermal flows. In terms of thermal capacity, tarmac causes heat to accumulate near the surface. It is quite evident that using pavement with a high thermal capacity and that readily stores thermal energy increases the intensity of the heat island effect. There is a close relationship between the temperature above an urban area being affected by thermal capacity and heat release. During our research of the heat island's profiles, thermal capacity was determined to be the most important source of an urban heat island being created. On-site surveying and the literature review verified that the effect of plants lowering the temperature is a complex aspect, and so this study considers the role of enthalpy in urban heat islands. The part plants play is energy conversion occurs between the surface and air while the effect of evapotranspiration causes changes in latent heat. Plants can mitigate the enthalpy of dry air of an urban area by converting thermal energy into enthalpy of moist air. However, plants are not effective at lowering the enthalpy of moist air, so Taiwan, which is located in a subtropical Asian climate, must consider issues related to latent heat, as the enthalpy of moist air impacts the comfort of those who live on the island.

The effects of an urban heat island can be mitigated by driving out the heat with ventilation from wind power and thermal buoyancy. However, the environmental conditions of urban areas vary, so an effective mitigation plan requires a focusing in on an area's relevant conditions.

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