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THE INTEGRATION OF HUMAN THERMAL COMFORT IN AN OUTDOOR CAMPUS LANDSCAPE IN A TROPICAL CLIMATE

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ABSTRACT: The purpose of this research is to study and compare outdoor spaces with different cooling devices in the tropical climate of the city campus in the CBD of Bangkok, Thailand. The study aimed to find the most comfortable outdoor space on a green campus, referring to the UI Green Metric World University Ranking indicators, with a case study of Chulalongkorn University, which is a wet, tropical area in the city center. The ratio of the area on campus that is covered with planted vegetation (lawns, gardens) is provided as a percentage of the total site area and is the subject of comparison. In particular, the microclimate seems to be an important criterion of the physical design features of an outdoor space: a) with cooling devices, such as shading and fountains, and b) without cooling devices, such as pavement and open lawn. The cooling effect of these devices, which are evaluated by the thermal comfort measurement results, responded according to the tropical environment of the campus. This study explains the micro/macroclimatic effects of the landscape features. The survey measured the meteorological conditions of the outdoor spaces. The study determined that the shortwave solar radiation and longwave radiation from different materials should play an important role in a new paradigm for green design and planning.

Keywords: Thermal comfort, Microclimate, Outdoor environment, Climatic effect, Green campus

1. INTRODUCTION

The UI Green Metric was launched in 2010 by Universitas Indonesia, in which the key objectives were initiated as the result of cooperative efforts among world university groups for managing and improving sustainability, as well as assisting in combating global climate change. Chulalongkorn University was ranked 15th in the world for the ‘city center’ campus setting category in 2016 and aims for a higher ranking in the upcoming years. Green campus planning involves landscape design of the campus outdoor environment. There is still a need to decrease energy consumption, especially for indoor heating, ventilation, and air conditioning (HVAC) systems. Thus, it leads to the following research questions regarding campus outdoor thermal comfort: 1) What are the human sensation responses to each outdoor space in the summer and rainy seasons? 2) What cooling devices should be designed for outdoor spaces in the tropical climate to provide the best thermal comfort?

Many studies on ergonomics have focused on thermal comfort in designing and arranging the things people use so that the people and things interact the most efficiently and safely, especially in the indoor environment. However, methods for making an outdoor environment comfortable are very limited, while outdoor and indoor comfort zones may differ from each other; therefore, adaptation or acclimatization to the outdoor environment should be studied [1]. This paper aims to integrate human thermal sensation and psychological responses according to the outdoor thermal environment evaluation index in the landscape architecture design and planning of an urban campus.

The factors influencing outdoor environmental comfort include the following: albedo, sky temperature, surface temperature, humidity, wind direction, air velocity, shortwave solar radiation and longwave radiation heat quantity. In addition, the measurements of sky and green upward and downward ratios from an orthographic photo of each site will be considered in this study. The design of an outdoor space usually depends on functional and other aesthetic concepts. The authors, who are from different research fields, have intensively utilized the year-long surveys from different seasons for their own aspects of research. This paper is intended to find a new paradigm in green design and planning to remediate the urban heat island effect, especially in campus planning, to improve the thermal environment from harsh to comfortable in order to draw potential activities to outdoor spaces reduce energy consumption in buildings.

2. EXPERIMENTAL DESIGN

The research surveys were designed to collect data from meteorological condition measurements of the outdoor spaces in both the summer and rainy seasons and the human physiological and psychological responses to those outdoor spaces. The surveys were performed during two days in March (summer/dry season) and in September (rainy/wet season) during the daytime only, from before noon to the afternoon, which is usually the peak hours of outdoor space occupancy for the campus. The aim of the very simple comparisons of the data is to find the most comfortable conditions in the outdoor spaces.

2.1 Measurement Procedures

The observation points and route patterns are shown in Fig. 1. For the comparisons, observation points were selected with consideration of the ground surface conditions, such as paved ground, green areas covered with plants, and water surfaces, and consideration of the condition of the sky factor due to buildings and trees. Six observation points were chosen in the summer season survey, and five observation points were chosen in the rainy season survey.

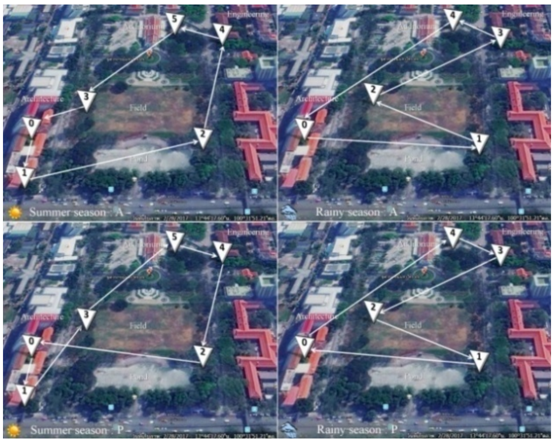

Fig.1 Site location maps and patterns of survey routes in the summer and rainy seasons during the peak hours (AM/PM).

2.2 Seasonally Related Factors

The observation points from the summer (March) and rainy seasons (September) were adjusted accordingly with the experiments. For example, the point at the open-air café was removed from the rainy season survey due to the unavailability of the new construction site, and the north playfield was intended to compare the difference between high and low sky factors, which were identified by the surrounding conditions (Table 1-2).

Table 1 Summary of summer season observation points

Summer		Surface: Ground	Surface: Sky		
0	**Building court**	Concrete	Eaves		
1	**Open-air café**	Wooden deck	Awning / Trees		
2	**Pond side**	Grass / Pond	Trees		
3	**North playfield**	Grass / Bare ground	Trees		
4	**Engineering bldg**	Concrete pavement	Sunshade / Trees		
5	**Auditorium plaza**	Concrete pavement	Open		
		Surrounding: North	**East**	**South**	**West**
0	**Building court**	Building	Building	Building	Building
1	**Open-air café**	Building	Building	Open	Wall / Tree
2	**Pond side**	Open	Open	Trees	Trees
3	**North playfield**	Open	Open	Trees	Open
4	**Engineering bldg**	Open	Building	Trees	Building
5	**Auditorium plaza**	Building	Open	Open	Open

Table 2 Summary of rainy season observation points

Rainy		Surface: Ground	Surface: Sky		
0	**Building court**	Concrete	Eaves		
1	**Pond side**	Grass / Pond	Trees		
2	**North playfield**	Grass / Bare ground	Open*		
3	**Engineering bldg**	Concrete pavement	Sunshade / Trees		
4	**Auditorium plaza**	Concrete pavement	Open		
		Surrounding: North	**East**	**South**	**West**
0	**Building court**	Building	Building	Building	Building
1	**Pond side**	Open	Open	Trees	Trees
2	**North playfield**	Open	Open	Open*	Open
3	**Engineering bldg**	Open	Building	Trees	Building
4	**Auditorium plaza**	Building	Open	Open	Open

2.3 Site-Related Factors

When considering the thermal sensations of humans, it is necessary to include air temperature as well as the environmental elements of thermal radiation, convection, humidity, and heat conduction. Briefly, a strong solar radiation gives a feeling of being hot, a strong wind gives a feeling of being cool, high humidity gives a feeling of being unpleasantly warm and moist (muggy weather), and a heated ground surface that cannot be touched makes us feel very hot. Kurazumi et al. [2]-[5] revealed the relationship between the physiological and psychological responses of humans and invented the enhanced conduction-corrected modified effective temperature (ETFe) as the outdoor thermal environment evaluation index, and they clarified in many of their research papers that the variables that affect the thermal sensations are heat conduction, humidity, shortwave solar radiation, air velocity, heat conduction, and humidity.

Air temperature, humidity, wind direction, air velocity, shortwave solar radiation heat quantity, longwave radiation heat quantity, and ground surface temperature were measured. The air temperature and humidity were measured at a height of 90 cm above the ground by means of an Assman ventilated psychrometer. For the air velocity, the prevailing wind direction was measured for 5 min at a height of 120 cm above the ground by means of a three-dimensional ultrasonic anemometer. When the wind was very gentle, the average air velocity was measured for 5 min at a height of 120 cm above the ground by a non-directional anemometer and the three-dimensional ultrasonic anemometer.

The shortwave thermal radiation heat quantity in the regions from the visible to near-and-mid-infrared and the terrestrial thermal radiation in the far infrared region were measured, and the thermal radiation heat quantities in the downward and upward directions were measured at a height of 90 cm above the ground by long and shortwave radiometer. The ground surface temperature was measured by a radiation thermometer.

The sky factor was measured by a photograph of the sky taken 120 cm above the ground at the observation point using a fisheye lens with an orthographical projection format and a 35 mm digital SLR camera. The albedo, sky temperature, and surface temperature were calculated from each directional component of the shortwave thermal radiation heat quantity and the longwave thermal radiation heat quantity. The abbreviations and the meanings are as follows.

Ta is the range of the air temperature. Tf is the range of the ground surface temperature near the human body. RH is the relative humidity. Va is the air velocity. RSdwn is the downward shortwave solar radiation. RSup is the upward shortwave solar radiation. RLdwn is the downward longwave radiation. RLup is the upward longwave radiation.

The influence of shortwave solar radiation in the outdoor environment appears to be strong in the summer, when the air temperature is higher than the skin temperature of the human body and evaporation is the only means of dissipating heat [2].

2.4 Human-Related Factors

Subjects moved on foot to the observation points without planning, in order to reduce mental fatigue at the slow walking speed (approximately 0.7 m/sec). They were then exposed to the thermal environment in a standing posture. Skin temperatures were measured as physiological conditions for the human body by a thermistor thermometer. Skin temperature was measured at the positions of the head, trunk, arm, hand, thigh, lower leg and foot. The subjects freely selected their clothing to be suitable to the weather on the measurement day. The clothing quantity of the subjects was constrained by the clo value by layering the clothing reported by the subjects. As a psychological condition for the human body, the psychological response was measured after staying at the observation point for 5 min by means of rating the whole-body thermal sensation (cold-hot) and the whole body thermal comfort (comfortable-uncomfortable) on a linear scale, as in Kurazumi et al 2011.

2.4.1 The Cooling Effect Conditions and the Thermal Environment Stimuli

Urbanization is a major cause of the urban heat island (UHI) phenomenon, related to a high percentage of low-albedo and impermeable surfaces, a reduction in the cooling effect of shading, built-up areas and especially the urban canyon, where heat is reradiated and reflected to the surrounded environment [6].

Planners always include shade trees wherever possible as a strategy to reduce heat islands and improve the outdoor environment in three ways: through shading, evapotranspiration, and wind shielding [7],[8]. The studies in many regions confirm that tree shade is an ecological solution to reduce both the mean radiant and surface temperature, as tree canopy can filter and absorb solar radiation and has the greatest affect a human's thermal comfort or physiological equivalent temperature (PET) [7],[9].At the macro scale, urban parks have been demonstrated to have a significant cooling effect that is strongest for land surface temperatures of surrounding urban areas as far as 860 m from the park boundary[6].

While pavements with light-colored surfaces can offset or reverse the heat island due to a high solar reflectance and high thermal emittance, and they can also reduce the temperature of the surface, which reduces the urban temperature and improves the urban air quality during the summer season [6],[11],[12],[13].

2.4.2 Human Physiological and Psychological Responses

There was a study showing that acclimatization did not have a significant difference on the psychological reaction when the subject could not tolerate the environment if the temperature was greater than 40˚C [4]. In addition, Thai people from a tropical region perceive an ETFe of up to approximately 35˚C to be a moderate thermal environment but cannot tolerate the temperature of approximately more than 40˚C [5] or 3˚Chigherthan normal body temperature or normothermia = 36.8 ±0.7 °C. Therefore, designers of effective outdoor environments should be aware of the harsh environment and consider avoiding alternatives and factors that can create heat radiation, especially during the summer.

3. RESULTS OF EACH SITE'S THERMAL ENVIRONMENT

After data calibration, the results from measurements were compared for the different methods to illustrate the effects of site conditions on human thermal comfort. The results after comparing three key issues of season, site, and human-related factors were to find the highest potential thermal comfort in the outdoor environment on the urban campus.

3.1 Site Cooling Effects

The most significant factors that explain the site cooling effects are as follows: 1) the sky factor, 2) the U-green factor, and 3) the D-green factor. From Fig. 2, ground and sky orthographic photos of the sites show different cooling conditions in different spaces, especially ground cover and pavement materials from the ground photos, building canyons and tree canopy from sky photos.

Thereafter, the sky factor and U-green / D-green factors have been simulated. The sky factor is defined as the ratio of the configuration factor of sky to the semi-celestial sphere. The U-green factor is defined as the ratio of the upward green, water surface and similar solid angles to the semi-celestial sphere solid angle. The D-green factor is defined as the ratio of the downward green, water surface and similar solid angles to the semi-celestial sphere solid angle. According to Fig. 3 and Fig. 4, the sites with the highest D-green factor are the pond site and the north playfield, where the ground is covered with grass and water or is bare ground. The U-green factor for each site shows the tree canopy coverage ratio. Therefore, at the north playfield site, when the measurement point was moved from under the trees to the field, the sky factor was significantly higher. In addition, the auditorium site has a higher sky factor and a lower D-green factor, and thus, it tends to be directly exposed to the radiation.

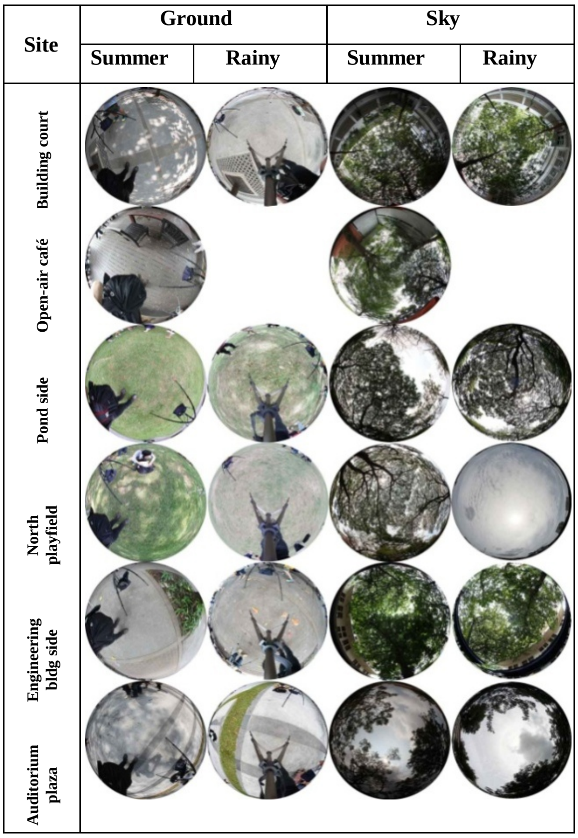

Fig. 2 Ground and sky photos of the sites with different cooling conditions

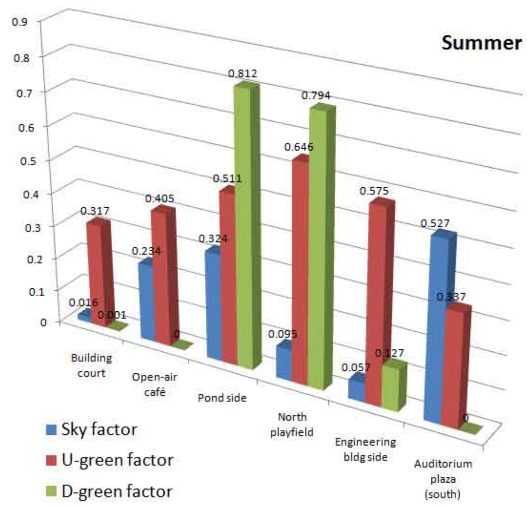

Fig. 3 [Summer season] Characteristics of the sites with different cooling conditions

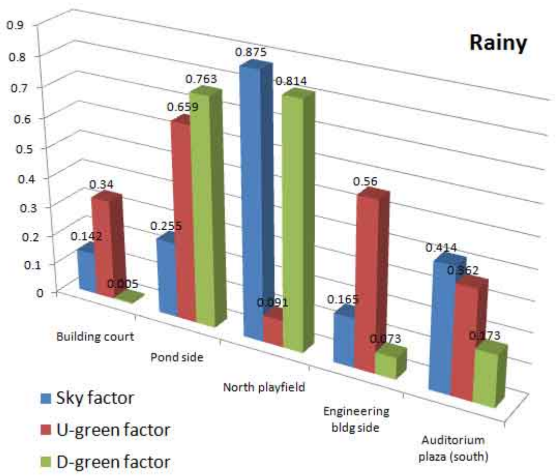

Fig. 4 [Rainy season] Characteristics of the sites with different cooling conditions

Together with the sky factors and green factors, at each site, other factors related to the albedo effect were measured in order to explain the cooling effect at the sites (Table 3). These factors included the mean values of RSdwn (downward shortwave solar radiation), RSup (upward shortwave solar radiation), RLdwn (downward longwave radiation), RLup (upward longwave radiation), Ta (air temperature), Tf (ground surface temperature), RH (humidity), Va (air velocity), and Tf-Ta (cooling effect temperature). The underlined numbers are among those presenting a cooling effect, and conversely, the bold numbers are those presenting a harsh thermal effect.

4. DISCUSSION OF THE INTEGRATION OF HUMAN THERMAL COMFORT AND SITECHARACTERISTICS

We assumed that site characteristics of outdoor space design as well as their surroundings are the key factors that influence human thermal comfort. The results from the meteorological conditions of the sites show that in both the summer and rainy seasons, the lesser cooling condition is significant at the auditorium at the south side plaza, where the Tf-Ta is very high.

Table4 [Summer season] Mean temperature

	Time	Ta[℃]	Tf[℃]	difT	Mean
0-Buildingcourt	10-1150	30.1	30.04	-0.06	3.53
0-Buildingcourt	10-1330	30.5	35.61	5.11	
0-Buildingcourt	10-1533	30.3	30.93	0.63	
0-Buildingcourt	10-1716	29.5	34.49	4.99	
0-Buildingcourt	11-1045	29.5	32.84	3.34	
0-Buildingcourt	11-1226	31.2	35.04	3.84	
0-Buildingcourt	11-1417	31.6	35.47	3.87	
0-Buildingcourt	11-1604	31.0	37.49	6.49	
1-Open-aircafé	10-1206	30.0	31.67	1.67	4.70
1-Open-aircafé	10-1552	31.1	36.52	5.42	
1-Open-aircafé	11-1104	30.0	35.85	5.85	
1-Open-aircafé	11-1438	32.1	37.97	5.87	
2-Pond side	10-1224	30.2	32.68	2.48	1.93
2-Pond side	10-1659	29.6	31.82	2.22	
2-Pond side	11-1209	30.8	32.75	1.95	
2-Pond side	11-1456	31.3	32.37	1.07	
3-North playfield	10-1316	30.2	35.28	5.08	5.35
3-North playfield	10-1610	29.9	34.70	4.80	
3-North playfield	11-1120	30.5	34.87	4.37	
3-North playfield	11-1549	31.4	38.55	7.15	
4-Engineering	10-1242	30.2	33.72	3.52	3.80
4-Engineering	10-1642	29.6	34.78	5.18	
4-Engineering	11-1153	30.3	33.68	3.38	
4-Engineering	11-1515	31.5	34.61	3.11	
5-Auditoriumplaza	10-1257	30.9	41.08	10.18	12.92
5-Auditoriumplaza	10-1628	29.9	41.36	11.46	
5-Auditoriumplaza	11-1139	30.8	47.23	16.43	
5-Auditoriumplaza	11-1530	32.3	45.92	13.62	

It is interesting that the sites, which are surrounded with buildings and pavement, such as the building court and the engineering building side, have very high RLdwn radiation values. However, the open field area with grass or bare ground, such as the

Table 3 Meteorological conditions of the sites with different cooling conditions

	Site[ND]	RSdwn [W/m2]	RSup [W/m2]	RLdwn [W/m2]	RLup [W/m2]	Mean Va	Mean RH	Mean Ta	Mean Tf	Tf-Ta
Summer	0-Building court	20.32	4.67	**484.41**	482.61	**0.58**	61.51	30.10	30.04	-0.06
	1-Open-air café	47.58	3.36	484.24	488.76	0.69	60.87	30.00	31.67	1.67
	2-Pond side	107.24	26.05	478.67	478.92	0.95	61.09	30.20	32.68	2.48
	3-North playfield	136.20	35.64	479.79	489.40	1.52	**63.05**	30.20	35.28	5.08
	4-Engineering bldg side	28.63	3.60	482.99	484.68	0.79	62.48	30.20	33.72	3.52
	5-Auditorium plaza	**437.27**	**116.06**	462.90	**530.50**	1.61	61.02	**30.90**	**41.08**	**10.18**
Rainy	0-Building court	9.79	0.42	**482.76**	472.87	0.80	59.36	30.8	27.2	-3.6
	1-Pond side	82.40	17.94	481.67	479.84	**0.68**	61.44	30.8	29.9	-0.9
	2-North playfield	**581.36**	**96.92**	451.17	509.57	1.63	58.47	**31.5**	37.4	5.9
	3-Engineering bldg side	18.42	-0.82	482.53	479.57	0.83	**62.13**	30.5	30.4	-0.1
	4-Auditorium plaza	371.61	91.32	467.72	**511.83**	1.22	59.46	31.4	**38.7**	**7.3**

north playfield, has a very high RS value, both upward and downward, in addition to quite a high RLup but a very low RLdwn.

Table5 [Rainy season] Mean temperature

	Time	Ta[℃]	Tf[℃]	difT	Mean
0-Buildingcourt	16-1033	31.1	28.7	-2.4	-3.6
0-Buildingcourt	16-1211	31.6	20	-11.6	
0-Buildingcourt	16-1336	32.2	29.5	-2.7	
0-Buildingcourt	16-1512	30.8	28.5	-2.3	
0-Buildingcourt	17-0943	29.4	26.2	-3.2	
0-Buildingcourt	17-1107	30.2	27.2	-3.0	
0-Buildingcourt	17-1254	30.5	29.2	-1.3	
0-Buildingcourt	17-1419	30.5	28.3	-2.2	
1-Pond side	16-1054	31.4	30.8	-0.6	-0.9
1-Pond side	16-1455	31.2	30.6	-0.6	
1-Pond side	17-1050	30	29.1	-0.9	
1-Pond side	17-1312	30.6	29.2	-1.4	
2-North playfield	16-1114	32.5	38.7	6.2	5.9
2-North playfield	16-1441	31.2	34.7	3.5	
2-North playfield	17-1034	30.4	35.3	4.9	
2-North playfield	17-1327	32	40.8	8.8	
3-Engineering	16-1133	31.4	30.4	-1.0	-0.1
3-Engineering	16-1412	30.7	31	0.3	
3-Engineering	17-1017	29.8	29.3	-0.5	
3-Engineering	17-1344	30.2	30.9	0.7	
4-Auditoriumplaza	16-1149	32.5	37.1	4.6	7.3
4-Auditoriumplaza	16-1356	31.8	41.3	9.5	
4-Auditoriumplaza	17-1001	30.4	36.2	5.8	
4-Auditoriumplaza	17-1359	30.8	40.2	9.4	

5. CONCLUSION

Chulalongkorn University is aiming for a higher ranking on the UI Green Metric in the upcoming years. The landscape design of the urban campus outdoor environment still needs to decrease energy consumption, especially for the indoor HVAC system. The findings from the research integrated human sensation responses to each outdoor space in both the summer and rainy seasons and the meteorological conditions of the sites. The results show a significant finding in that cooling devices in a tropical climate can be designed for the best thermal comfort and that the spaces between buildings in this very high-density area could be used to create a comfortable zone for outdoor activities. The most interesting finding from this study is the very harsh thermal condition created by the paved outdoor space with less shade. Therefore, although the built-up area is the major cause of UHI, a court area between a group of buildings with tree canopies can offer a comfort zone in both the summer and the rainy season. An open field area is good as an infiltrated ground for water sensitive urban design (WSUD) and keeps the average temperature cool, as it is only covered with grass. The heat from shortwave solar radiation and longwave radiation, the so-called albedo effect and emissivity, should play an important role in human thermal comfort and the landscape design of outdoor spaces.

6. ACKNOWLEDGEMENTS

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