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A Comparison between In-situ PET and ENVI-met PET for Evaluating Outdoor Thermal Comfort

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ABSTRACT

Purpose: PMV, PET, and similar thermal comfort indices and microclimate modeling have recently become actively used to evaluate thermal comfort. This study will look at pedestrian roads with diverse spatial characteristics on university campus using the ENVI-met model as the base for onsite measurement. **Method**: The PET was used as the thermal comfort index. The first microclimate measures were collected on September 20, 2014, and the second microclimate measures were collected on June 1, 2015. The ENVI-met model was used at the same time. **Result**: As a results, Onsite measurement results differed depending on the PET spatial characteristics. The location associated with the most discomfort had a PET of 47.8°C. The spatial characteristics of this place included a with no shade. The most comfortable location had shade, and the PET was 24.6°C. When the ENVI-met model and onsite measurements were compared, similar patterns were found, but with a few differences at specific points; this was due to the limitation of using input materials such as trees, buildings, and covering materials with the ENVI-met model. This factor must be thoroughly considered when analyzing modeling results.

KEYWORD

열쾌적성
미기상 모델링
도시열섬
평균복사온도

Thermal comfort
Micro-climate modeling
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Mean radiant temperature

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1. Introduction

1.1. Background and Purpose of Study

As urbanization makes progress, natural paving decreases and artificial paving materials such as asphalt and concrete increase. Artificial paving materials with large heat capacity accumulate large amount of radiant energy on the surface and increased unevenness such as buildings impedes thermal radiation of radiant energy and ventilation, resulting in urban thermal environmental problems such as heat wave, heat island and tropical night in summer.[25] As the quality of life improves recently, citizens enjoying leisure, sports, etc. require comfort outdoor space.

The thermal environment of urban area is greatly influenced by topography, use of land, green area, etc.[11][14] As for the space like parks and sidewalks, changing the orientation and placement of street trees and nearby buildings can make the space comfortable. As design change is difficult and thermal environment elements such as temperature, humidity and wind speed cannot be adjusted easily in outdoor space, thermal environment shall be evaluated quantitatively in order to establish comfort environment.[11][14][17]

Many studies are being performed to evaluate thermal environment quantitatively. Among them, more than 40 types of thermal comfort indexes are used after Haldane suggested wet bulb temperature in 1905 in order to indicate comfort felt by human in a space objectively.

Thermal comfort is a state of mind which is satisfied with thermal environment and as there are many elements to be considered for evaluation of thermal comfort in outdoor space, it has been evaluated mostly on interior space with a small number of elements to be considered. Interest on thermal comfort in outdoor space has increased, however, and a variety of thermal comfort indexes such as PMV (Predicted Mean Vote: Fanger, 1972; ISO 7730, 2005)[22] and PET(Physiological Equivalent Temperature: Höppe, 1999)[23] which can evaluate thermal comfort in outdoor space are being developed, resulting in active study related to it. As tools for predicting the spatial distribution characteristics of thermal comfort by using micro-climate modeling such as ENVI-met and Rayman are used, attention on the improvement of thermal comfort in outdoor space is also increasing in respect of urban and environmental planning. As micro-climate modeling has a limit, however, in reproducing actual space or reflecting a variety of variables which occur in reality[8], accuracy must be verified by

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using in-situ measurement to ensure the reliability of results from micro-climate modeling analysis. Therefore, this study intends to compare the PET indexes of in-situ measurement and ENVI-met which is widely used for evaluation of thermal comfort in order to identify the accuracy of micro-climate modeling in regard to thermal comfort.

1.2. Consideration of Previous Studies

Literature search in regard to evaluation of thermal comfort by using in-situ measurement is as follows. If we look at Korean studies first, Lee et al.[13](2014), Ryu et al.[5](2013) performed in-situ measurement to verify the thermal environment improving effect of green trees and confirmed the effect of shade made by green trees on thermal comfort of human body by measuring SET* (Standard Effective Temperature) and average radiant temperature. Ahn et al.[9](2013) used WBGT (Wet Bulb Globe Temperature) to analyze the effect of shade of street trees on the thermal comfort of pedestrians by investigating the behavior of pedestrians and performing a survey. As above, thermal comfort evaluation through in-situ measurement has high accuracy as the current status of the actual space can be identified but has limitation in the evaluation of the entire space and requires much cost and time. It also has limitation in the design stage as the characteristics cannot be evaluated quantitatively before the external space is established.[16] To overcome the limitation of in-situ measurement, environmental prediction models such as Rayman and ENVI-met are developed and used for various purposes.[13][21] Lee et al.[14](2010), Lim et al.[15](2013), Jeon et al.[16](2010) used micro-climate modeling to analyze micro-climate characteristics evaluate thermal comfort in spaces like university campus, parks and condominium complex. Although micro-climate modeling has advantages of no limitation in space and time, possible comparison and prediction in the planning stage and a variety of scenarios set for analysis, the actual space is difficult to reproduce completely in modeling. Therefore, accuracy must be verified on the basis of actual measurements in order to use modeling.

If we look at foreign, previous studies in regard to verification of accuracy of modeling, Ng et al. [29](2012) analyzed the urban temperature reducing effect by changing spatial design according to the amount of green area for Hong Kong in order to verify the usability of ENVI-met modeling on the basis of in-situ measurements. Srivanit et al.[30](2013) corrected the ENVI-met model based on in-situ measurements and then analyzed the effect of green area on the improvement of thermal environment. In Korea, Song et al.[8](2014) compared weather elements of in-situ measurement and the micro-climate modeling (ENVI-met) according to the type of land use. As above, foreign previous studies are actively performed to verify the accuracy of the modeling and then evaluate thermal comfort. On the contrary, most of Korean studies analyzed thermal comfort by only using either actual measurement or modeling but study on verification of modeling is not sufficient.

2. Theoretical Consideration

2.1. Thermal Comfort

Thermal comfort is a state of mind which is satisfied with thermal environment.[18] The thermal comfort level of a human can be measured by considering the input and output of energy flow. Energy equilibrium equation which indicates energy flow is as shown in Expression 1.

Energy equilibrium = metabolism energy + solar radiation energy absorptions + earth radiation energy absorptions − heat loss due to evaporation − energy loss due to convection − emitted earth radiation energy (1)

If energy equilibrium is (+), it indicates hot state. If it is (-), it indicates cold state. If it is near 0, it indicates energy equilibrium and thermally comfortable state. Therefore, thermal comfort shall consider activity which influences metabolism energy, radiation energy, external thermal environmental elements (temperature, relative humidity and wind speed) and clothing which influences the absorption of heat. Radiation energy is measured as mean radiant temperature. Mean radiant temperature is a measure for expressing radiant heat and indicates the mean temperature of ambient surface where heat is exchanged with human body by radiation.[3]

2.2. PET

Indexes for evaluation of thermal comfort in certain space continue to be developed. Those developed until now include ET, ET*, SET*, DI, PMV and PET. These thermal comfort indexes have different elements considered and expression method and most of indexes were developed as those for evaluation of interior thermal environment and then index such as PET has been proposed by considering outdoor space.[28]

Table 1. Physiologically Equivalent Temperature (PET) Range (Matzarakis and Mayer, 1996)

PET(℃)	Thermal sensation	Physiological stress level
<4	very cold	extreme cold stress
4-8	cold	strong cold stress
8-13	cool	moderate cold stress
13-18	slightly cool	slight cold stress
18-23	comfortable	no thermal stress
23-29	slightly warm	slight heat stress
29-35	warm	moderate heat stress
35-41	hot	strong heat stress
>41	very hot	extreme heat stress

PET is an index applicable to outdoor space, widely used now and expressed in temperature unit(℃).[12] Elements required for calculation of PET include climate elements (physical elements) such as temperature, humidity, mean radiant temperature and air velocity and personal elements such as activity and clothing and comfort range is as shown in Table 1. 18~23℃ of PET indicates comfortable range. If PET is above and below the range, it indicates discomfort of hot and cold, respectively.

3. Method of Study

3.1. Location for Study

Walk space in a university campus located in Changwon, Gyeongsangnam-do has been selected as the location for study (latitude: 35°14′ N, longitude: 128°41′ E). The target site has been selected by considering spatial characteristics such as building, vegetation and paving material and convenience of in-site measurement by movement method(Fig. 1). The site also has a small size of 388m wide and 168m long, which is suitable for use of ENVI-met model.

(a) Open space

(b) Green space

(c) Resting place

(d) Mobile measurement equipment (Testo 480)

Fig. 1. Research location's Characteristics and measurement equipments

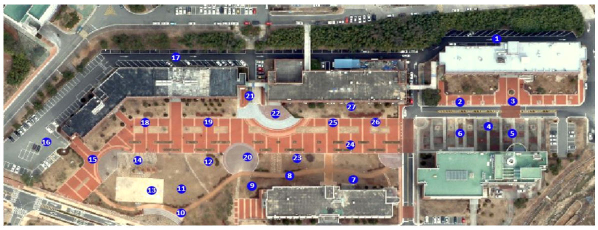
3.2. In-Situ Measurement of Micro-Climatic Data

Micro-climate measurement was performed two times to calculate PET. The first measurement was performed from 08:00 AM to 05:00 PM on September 20, 2014 and the second was performed from 10:00 AM to 04:00 PM on June 1, 2015. The measurement dates were selected by considering weather conditions such as cloud cover, temperature and airflow and environment where pedestrians can feel the heat, etc. Required time for the all measurement points is less than two hours and as difference in time for measurement points is generated by moving measurement, measurements according to elapse time were corrected by using Expression 2 and 3 in order for comparison among measurement points in the same time[8].

$$\alpha = \frac{\{X_f - X_s\}}{X_f} / (T_f - T_s) \quad (2)$$

$$Y = X - X \times (T - T_s) \times \alpha \quad (3)$$

Where α is correction coefficient, Xf is measurement at the last point, Xs is measurement at the start point, Tf is the last measurement time, Ts is the first measurement time, X is the measurement, T is time and Y is the corrected measurement.



(a) Measurement spot on September 20, 2014

(b) Measurement spots on June 1, 2015

Fig. 2. Measurement spots on 09/20/2014 and 06/01/2015

As shown in Fig. 2, 27 and 20 measurement points were selected for the first and second measurements by considering spatial characteristics such as paving material, shade, surrounding building and vegetation. Micro-climate such as temperature, relative humidity, wind speed and globe temperature was measured at the height of 1.2m by using the multi-purpose environmental measuring instrument (Testo 480) as shown in Fig. 1 and recorded in data log in the interval of 5 seconds. Temperature, relative humidity, wind speed and globe temperature are required to calculate PET and mean radiant temperature was calculated by using wind speed, globe temperature and temperature as shown in Expression 4. As globe temperature requires stabilization time compared with other elements, measuring time for each point has been set to be more than 8~10 minutes.

$$T_{mrt} = \left\{ (Tg + 273)^4 + \frac{1.1 \cdot 10^8 \cdot v_a^{0.6}}{\epsilon \cdot D^{0.4}} (Tg - Ta) \right\}^{1/4} - 273 \quad (4)$$

where T_{mrt} is the mean radiant temperature (℃);

T_g is the globe temperature(℃);

T_a is air temperature (℃);

D is the globe diameter (m);
V_a is the air velocity at the level of the globe (m/s);
ε is the emissivity of the globe (0.95 for a black globe).

3.3. ENVI-met Modeling

ENVI-met micro-climate model used in this study is a three-dimensional micro-climate analysis program where data on building, paving material and vegetation in urban space is entered in a grid form and the change of micro-climate such as temperature, humidity, radiant energy, air flow, flow of fluid, etc. due to surrounding environment can be expected in the unit of micro-scale.[31] ENVI-met can predict about 24~48 hours. Time resolution is more than 10 seconds and spatial resolution is 0.5~10m.[19][29] Two input data of IN(Input) File and CF(Configuration) File are required. IN file is an input file which establishes spatial characteristics such as the geographical location of the analysis site, material and height of buildings, type of vegetation and paving materials. The size of the target site was set to be 388m wide and 168m long and the spatial resolution, which indicates the size of one lattice cell was set to be 2m. Information on the height of buildings, paving type and vegetation was digitized by using aerial orthophotograph (Fig. 3). CF file is a file for entering analysis and modeling time and initial weather data such as temperature, humidity, wind speed and direction was set as shown in Table 2. ENVI-met model version 3.5 was used and Leonardo 2014 was used to extract and analyze data.

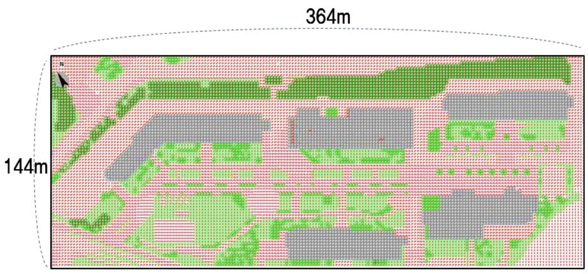


Fig. 3. ENVI-met IN file (Input file) setting

Table 2. ENVI-met CF file (configuration file) setting

Parameter	2014.09.20	2015.06.01
Simulation date	2014.09.20	2015.06.01
Simulation time	06:00~18:00	06:00~18:00
State time	60	60
T_a (Air temperature)	299.3°K	300.5°K
RH, Relative Humidity	32%	53%
V, wind speed	1.6m/s at 10m height	0.9m/s at 10m height
Wind direction	West	West
Roughness Length Zo at Reference point	0.1	0.1

3.4. PET Calculation by Using RayMan

As shown in Fig. 4, PET can be calculated by using RayMan 1.2 model and entering the latitude and longitude of the position where micro-climate elements were measured, temperature, humidity, wind speed, cloud cover and mean radiant temperature .[27]

As for the personal variables such as metabolism and clothing, activity was set to be 2.0Met(115W), which indicates slow walk activity by considering that the target site is walk space. Clothing was set to be 0.7clo, which indicates wearing light tropical clothes by considering the weather at the time of measurement. Spot-specific PET values calculated on the basis of in-situ measurements and micro-climate elements from ENVI-met modeling were compared by using RMSE (Root Mean Square Error).

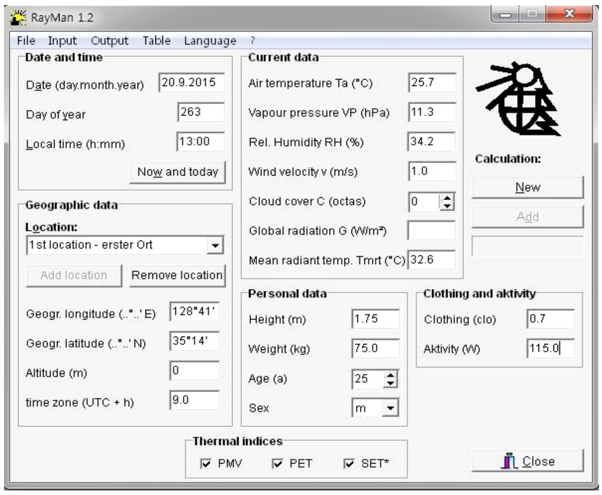


Fig. 4. Rayman model setting

4. Results of Study and Considerations

4.1. Results of In-Situ PET Calculation

PETs for 27 spots according to the first in-situ measurement (Sep 20, 2014) are as shown in Table 3 and each PET is based on 01:00 PM and 03:00 PM which are the times moving measurement has started. Micro-climate data at 01:00 PM showed 29.0℃ of temperature, 29.4% of relative humidity and 1.5m/s of wind speed on average, indicating similar results in every spot and mean radiant temperature(T_{mrt}) showed difference according to the spatial characteristics of measurement points. The PET of Spot 27 where paving material is grass and is close to a building was the most discomfortable level (44.1℃). Although the temperature, humidity and wind speed of the spot were similar to those of other spots, mean radiant temperature was very high (81.6℃). It is judged to result from the fact that Spot 27 is influenced by earth radiation energy and solar radiation energy as it is close to a building if compared with other spots. The spot with the most

Table 3. PET measurements on September 20, 2014, presence of shade

Spot	Paving Materials	13:00			15:00			Spot	Paving Materials	13:00			15:00		
		Shade Types	PET (℃)	T_{mrt} (℃)	Shade Types	PET (℃)	T_{mrt} (℃)			Shade Types	PET (℃)	T_{mrt} (℃)	Shade Types	PET (℃)	T_{mrt} (℃)
1	Asphalt	Building	27.6	32.6	Building	25.5	36.3	15	Clay Block	x	40.5	52.0	x	30.5	55.6
2	Clay Block	x	39.9	57.6	x	32.8	46.5	16	Asphalt	x	40.6	65.5	x	30.5	60.5
3	Clay Block	x	37.4	76.6	x	35.0	63.2	17	Asphalt	Building	30.2	36.1	Building	25.9	28.4
4	Clay Block	Tree	30.8	41.1	Tree	26.3	39.0	18	Clay Block	x	37.4	58.6	x	29.5	50.8
5	Clay Block	Building	27.8	34.7	Building	24.7	31.3	19	Clay Block	x	42.0	70.3	x	30.5	57.4
6	Clay Block	Building	27.1	31.4	Building	24.6	29.3	20	Wooden deck	x	40.3	70.8	Tree	25.0	43.1
7	Grass	Building	27.3	29.4	Building	25.3	28.0	21	Asphalt	x	42.7	72.0	x	30.9	51.3
8	Soil	Building	26.1	29.1	Building	26.1	26.3	22	Concrete	x	38.1	62.4	x	29.5	56.0
9	Grass	x	36.8	48.0	x	32.8	48.5	23	Grass	Tree	36.0	48.4	x	28.7	44.4
10	Soil	x	40.6	64.0	x	33.4	56.5	24	Clay Block	x	39.9	82.3	Building	25.5	33.1
11	Grass	x	36.6	64.5	Tree	28.4	46.9	25	Clay Block	x	40.3	53.2	x	29.1	39.6
12	Grass	x	39.5	58.3	x	31.5	60.6	26	Clay Block	x	39.6	59.1	x	27.7	57.0
13	Urethane	x	41.1	71.9	x	31.1	76.0	27	Grass	x	44.1	81.6	x	31.8	43.5
14	Stone slab(gray)	x	40.3	67.6	x	32.3	37.7								

Table 4. PET measurements on June 1, 2015, presence of shade

Spot	Paving Materials	12:00			14:00			Spot	Paving Materials	12:00			14:00		
		Shade Types	PET (℃)	T_{mrt} (℃)	Shade Types	PET (℃)	T_{mrt} (℃)			Shade Types	PET (℃)	T_{mrt} (℃)	Shade Types	PET (℃)	T_{mrt} (℃)
1	Asphalt	x	38.2	58.2	x	46.0	72.0	11	Wooden deck	x	46.1	74.2	x	47.8	72.2
2	Clay block	Tree	36.2	55.2	x	42.1	72.7	12	Grass	Tree	34.8	40.5	Tree	35.0	48.9
3	Clay block	x	41.5	67.0	x	41.2	71.0	13	Grass	x	44.9	69.3	x	41.9	68.0
4	Clay block	Tree	33.1	45.8	Tree	32.0	46.7	14	Urethane	x	43.8	65.9	x	46.9	68.3
5	Clay block	x	43.4	66.4	Building	32.4	42.6	15	Asphalt	x	44.7	72.6	x	42.8	73.1
6	Grass	Tree	31.2	44.6	Building&Tree	30.5	34.2	16	Asphalt	x	42.8	62.3	Building	32.5	37.3
7	Grass	x	39.1	57.0	x	38.3	60.1	17	Grass	x	45.8	63.7	x	42.0	63.7
8	Grass	x	34.0	62.0	x	42.4	68.3	18	Clay block	x	43.8	67.4	x	44.8	73.3
9	Grass	Tree	39.7	57.7	x	41.5	60.7	19	Asphalt	x	42.6	57.1	x	41.9	67.9
10	Clay block	x	38.6	56.4	x	39.4	59.4	20	Concrete	x	38.4	59.5	x	38.1	60.7

comfortable level was Spot 8 with 26.1℃ of PET. The spatial characteristics of the spot is that paving material is soil and there is shade caused by a building. According to the results of measurement at 03:00 PM, 27.5℃ of temperature, 32.3% of relative humidity and 1.7m/s of wind speed were found on average and Spot 3 has the highest PET of 35.0℃. It is judged to result from the fact that Spot 3 has no shade and open spatial characteristics, causing the effect of solar radiation energy.

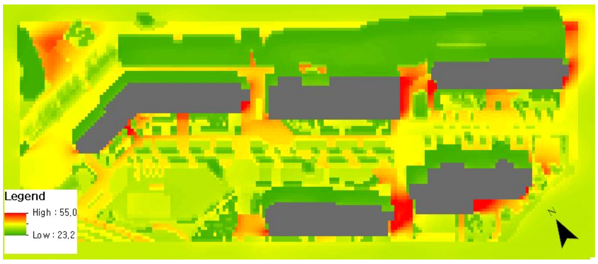
Next, results from the second in-situ measurement (June 1, 2015) were obtained by dividing into 12:00 PM and 02:00 PM on the basis of time moving measurement started. First, 12:00 PM showed 29.8℃ of mean temperature, 43.6% of humidity and 1.3m/s of wind speed and mean radiant temperature showed much difference according to the characteristics of measurement spots. Spot 11 with wooden deck as paving material and exposed to sunlight showed the most discomfortable level of 46.1℃. The mean radiant temperature of Spot 11 was 74.2℃ which is highest and 29.5℃ of temperature, 1.9m/s of wind speed and 43.9% of humidity were similar to mean values. It is judged to result from very large earth radiation energy emitted by wooden deck. Spot 6 with the most comfortable level of PET had grass as the paving material and was shaded by trees. Temperature of Spot 6 was 27.7℃, which was the lowest. The mean radiant temperature was second lowest (44.6℃) and humidity was 48.6%, which is higher than the average (43.6%). The wind speed was 1.4m/s similar to the average.

As for Spot 17 with the second highest PET, it is judged to result from the fact that it is influenced by the solar radiation energy and earth radiation energy emitted by a building at a position close to the building. Spot 9 which has similar characteristics to Spot 17 was influenced by earth radiation energy as it is close to a building. It was more comfortable, however, due to the shade of trees. While 33.8℃ of average PET was found in other spots with shade at this time, Spot 9 showed poor level (39.7℃). It is judged to result from the spot being influenced by earth radiation energy emitted by the building if compared with other spots. 02:00 PM showed 30.5℃ of temperature, 40.1% of relative humidity and 1.5m/s of wind speed on average and the spot with the highest PET was Spot 11 with 47.8℃ of PET which had wooden deck as the paving material and was influenced by sunlight. Although temperature, humidity and wind speed were similar to averages, it is judged that very high mean radiant temperature (72.2℃) influenced PET. On the contrary, Spot 6 showed 30.5℃ of PET which had grass as the paving material and shaded by trees and buildings, resulting in the most favorable thermal comfort.

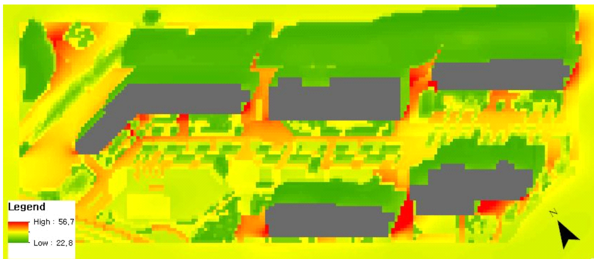
4.2. Results of ENVI-met PET Calculation

Micro-climate and PET by using ENVI-met were predicted as shown in Fig. 5 according to the date and reference time of 1st and 2nd in-site measurements. If we look at the results of micro-climate measurement predictions by using ENVI-met modeling on the basis of the 1st measurement date (Sep 20, 2014), the temperatures of 01:00 PM were 23.7℃ (mean), 25.3℃ (max.) and 16.9℃ (min.) and showed similar values except four spots with the minimum value. The mean, maximum and minimum of humidity were 57.9%, 61.6% and 53.2%. The mean, maximum and minimum of wind speed were 1.4m/s, 2.65m/s and 0.0m/s. The mean radiant temperature was predicted to be 48.3℃ on average and showed much difference due to solar energy and earth radiation energy according to the spatial characteristics of each spot. Results of PET calculation by using ENVI-met modeling at 01:00 PM are as shown in Fig. 5(a). Predicted PET has the maximum of 55.0℃ and minimum of 23.2℃. Spots with comfortable level were those included in the shade area of trees and buildings and those located in green area. Spots with discomfortable level were those located between buildings and those which had clay block and asphalt as the paving material. If we look at modeling results at 03:00 PM, temperatures showed 24.1℃ (mean), 25.7℃ (max.) and 16.9℃ (min.). The mean, maximum and minimum of humidity were 62.0%, 66.3% and 56.9% and the mean, maximum and minimum of wind speed were 1.4m/s, 2.6m/s and 0.0m/s. The average, maximum and minimum of mean radiant temperature were 49.6℃, 70.9℃ and 24.5℃. The results of PET calculation by using ENVI-met modeling at 03:00 PM are as shown in Fig. 5(b). 03:00 PM had wider shade area due to lowered solar altitude compared with 01:00 PM , resulting in wide comfortable area. In Both times, it has been found that mean radiant temperature was predicted to have the most similar pattern, having great effect on PET. Temperature and wind speed were predicted to be high and low, respectively for space between buildings with high PET and those which had artificial paving as the paving material.

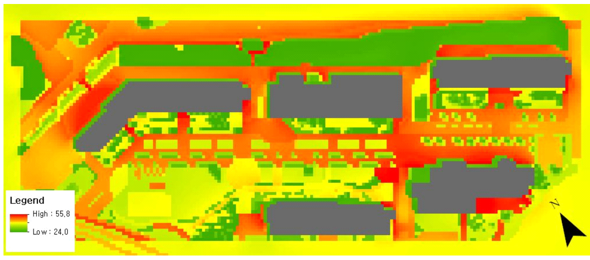
If we look at the results of ENVI-met modeling on the basis of the 2nd measurement date (June 1, 2015), the temperatures of 12:00 PM were 29.5℃ (mean), 30.4℃ (max.) and 29.1℃ (min.) and showed similar values in 20 sports. The mean, maximum and minimum of humidity were 61.5%, 66.3% and 558.4%. The mean, maximum and minimum of wind speed were 0.5m/s, 1.03m/s and 0.16m/s and predictions were similar in most of spots. The mean radiant temperature was predicted to be 54.2℃ on average and showed much difference due to solar energy and earth radiation energy according to the spatial characteristics of each spot. Results of PET calculation by using ENVI-met modeling at 12:00 PM are as shown in Fig. 5(c). Predicted PET has the maximum of 55.8℃ and minimum of 24.0℃.



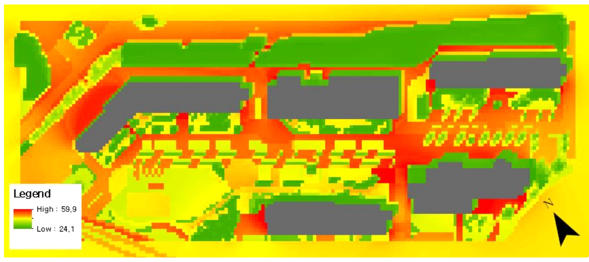
(a) ENVI-met PET map at 1p.m.. on September 20, 2014



(b) ENVI-met PET map at 3p.m.. on September 20, 2014



(c) ENVI-met PET map at 12p.m.. on June 1, 2015



(d) ENVI-met PET map at 2p.m.. on June 1, 2015

Fig. 5. ENVI-met PET maps on 09/20/2014 and 06/01/2015

The mean radiant temperature showed 74.1℃ of maximum value and 30.9℃ of minimum value and much difference according to the spatial characteristics of the prediction spots. PET prediction results at 02:00 PM showed 59.9℃ of maximum and 24.1℃ of minimum as shown in Fig. 5(d) and wide comfortable area compared with 12:00 PM. Spots with discomfortable level were those with asphalt, concrete and clay block as the paving material as in 12:00 PM. Spots with relatively comfortable level were those with green area, those shaded by buildings and trees, etc.

4.3. Comparison of Results from In-Situ and ENVI-met PET Calculations

If we look at results from in-situ measurement and PET calculations by using ENVI-met modeling on the basis of RMSE as shown in Table 5, 01:00 PM of the 1st measurement date (Sep 20, 2014) showed temperature: 5.8℃, humidity: 28.9%, wind speed: 1.0m/s, Tmrt: 14.2℃ and PET 6.2℃. 03:00 PM showed temperature: 4.4℃ , humidity: 29.9%, wind speed: 1.1m/s, Tmrt: 13.8℃ and PET 6.4℃. The RMSE of in-situ measurements and modeling results at 12:00 PM of the 2nd measurement date (June 1, 2015) showed temperature: 1.5℃, humidity: 18.4%, wind speed: 1.0m/s, Tmrt: 10.6℃ and PET 5.1℃. 02:00 PM showed temperature: 1.4℃ , humidity: 22.4%, wind speed: 1.1m/s, Tmrt: 7.7℃ and PET 6.1℃.

Table 5. RMSE by each factors at 20/09/2015 and 1/06/2015

Date	Time	air temperature(℃)	humidity(%)	wind speed (m/s)	Tmrt (℃)	PET (℃)
20/9/2014	1 p.m.	5.8	28.9	1.0	14.2	6.2
	3 p.m.	4.4	29.9	1.1	13.8	6.4
1/6/2015	12 p.m.	1.5	18.4	1.0	10.6	5.1
	2 p.m.	1.4	22.4	1.1	7.7	6.1

Results from comparison of ENVI-met model and in-situ PETs are as shown in Fig. 6. PET of actual site measurement is expressed as in-situ PET in the result graph. If we look at 01:00 PM on the 1st date (Sep 20, 2014), PETs of in-situ measurements are higher than ENVI-met model PETs in most spots. If we look at micro-climatic elements extracted from ENVI-met, there is no large variation in wind speed and humidity but temperature showed more than 10℃ of difference from in-situ measurement in some spots. And, Tmrt showed much difference according to the characteristics of measurement spots. While Spot 9, one of those with much difference showed 36.8℃ of in-situ PET, ENVI-met PET was about 7.0℃ higher (43.8℃). Tmrt calculated from ENVI-met at this spot was 68.8℃, which is very higher than in-situ measurement (48.0℃). It is judged to result from that there are many trees around in actual measurement but the scope of shade is not correctly expressed in modeling. 03:00 PM showed similar results if compared with 01:00 PM and large difference in some spots as shown in Fig. 6(b). Spots with much difference are Spot 9, 20 and 24. Spot 20 and 24 had the shade of trees and buildings, respectively in actual measurement but modeling did not express the scope of shade correctly, resulting in those differences. It is judged that Spot 9 had insufficient representation of surrounding trees as in 01:00 PM. It is judged that large difference between in-situ measurements and modeling results is due to the error in the scope of shade by trees and buildings and limitation in resolution due to the pixel size of modeling.

On the 2nd measurement date (June 1, 2015), PET values obtained by in-situ measurement and modeling were similar in most spots but were different in some spots. If we look at 12:00 PM, modeling results were overestimated in Spot 1, 3, 10 and 20 as shown in Fig. 6(c). If we look at the characteristics of these spots, all four spots had no shade but Spot 1, 3 & 10 and 20 had asphalt, clay block and concrete as the paving material. It is judged to result from the fact that mean radiant temperature was predicted excessively which has great effect on PET calculation in these spots. On the contrary, Spot 11, 13 and 18 showed lower modeling values than in-situ measurements. If we look at them in more detail, Spot 11 and 17 had no direct shade during actual measurement but were influenced by surrounding buildings. It is also judged to result from that trees were planted around and modeling predicted influence by trees due to the vague boundary of tree shade. Spot 13 had grass as the paving material, was of wide space and in-situ PET was very discomfortable but modeling expressed the grass to be comfortable, resulting in much lower value than in-situ measurement. If we compare in-situ measurement at 02:00 PM and modeling PET, Spot 3, 10, 12 and 20 were predicted excessively as shown in Fig. 6(d). Spot 10 and 20 are judged to result from the fact that mean radiant temperature which has great effect on PET is predicted excessively. Spot 12 was tree shade in actual measurement but modeling evaluated less impact of trees, resulting in low thermal comfort. Spot 3 is judged to show very high PET as effect of earth radiation energy and solar radiation energy are reflected in the modeling.

As above, temperature, humidity, wind speed and mean radiant temperature obtained by in-situ measurement and ENVI-met modeling are influenced by spatial characteristics. According to the results of application of ENVI-met modeling to the site for study, mean radiant temperatures tend to be predicted to be higher than in-situ measurements and it is judged to result from the fact that the scope of shade, degree of blocking sunlight, etc. according to the height of buildings and leaf area index, tree crown and height of trees are not reflected in ENVI-met modeling sufficiently. It is also judged that modeling results are influenced by the fact that physical current information such as the paving material, trees and building of the site is not reflected accurately due to the limitation in spatial resolution of input data. It is necessary to interpret modeling results by considering sufficiently the fact that ENVI-met program has limitation in reflecting the characteristics of plants such as grass and trees as input data.

5. Conclusion

This study performed the 1st and 2nd measurements on Sep 20, 2014 and June 1, 2015, respectively for walk space in a university campus , calculated in-situ and ENVI-met modeling PETs and compared them in order to verify the accuracy of ENVI-met micro-climate model for evaluation of thermal comfort for spatial characteristics.

According to the in-situ measurements, PET showed difference according spatial characteristics. In summer, there was large difference in thermal comfort according to the blocking of sunlight. In particular, blocking by buildings showed more comfortable level than blocking by trees. It is judged to result from the fact that solar radiation energy is more blocked by building than by trees. If a spot is close to a building when it is influenced directly by solar radiation energy, it showed very poor thermal comfort if compared with other spots as it is influenced by solar radiation energy and earth radiation energy which is emitted by the ground surface.

According to the comparison of ENVI-met PET and in-situ PET, they showed similarity overall but large difference in some spots. Spots with large difference had mean radiant temperature predicted to be very high and it resulted in high PET. First, it is judged that large differences result from the fact that ENVI-met modeling had a tendency of excessive prediction in space which had artificial paving such as asphalt and concrete as the paving material and ENVI-met showed low accuracy in the scope of shade made by buildings and trees when the measurement spot is influenced by shade. Second, humidity among micro-climate elements showed overall difference between actual measurements and modeling values and wind speed showed large difference as it does not show constant pattern due to the extensive impact of local wind, regional wind, etc. Therefore, it is judged that in these cases, impact of surrounding areas shall be considered by using weather model of local scale for the target site instead of long-term weather observation before using micro-climate modeling such as ENVI-met.

While previous studies compared modeling and in-situ measurements according to time change at the same spot, this study has a meaning that it considers a variety of spatial characteristics. There was limitation in reproduction of actual space in modeling as urban area consists of various and complex spatial characteristics. Vegetation, buildings, etc. shall be represented in 3D to predict the flow of radiation energy more accurately and it is expected that accuracy will be increased as modeling program improves.

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