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Validation of ENVI-met PMV values by in-situ measurements

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1. Introduction

The increased use of artificial paving materials, such as concrete and asphalt, has contributed to the deterioration of the thermal environment of urban areas. Moreover, it has caused changes in the microclimate of those areas, such as heat waves in summer, and the 'heat island effect'. Problems caused by changes in the microclimate bring about discomfort for urban dwellers and pedestrians and increase the demand for spaces with more comfort. Thermal comfort is the mental state of feeling satisfied with the ambient environmental conditions. In order to improve the thermal comfort of an urban space, waste heat needs to be reduced and the evapotranspiration of the urban green spaces needs to be increased.[1] Furthermore, the additional heat from artificial paving materials should be reduced to a minimum. Therefore, rather than understanding the thermal environment only by measuring the microclimate, human psychological and physiological factors should also be considered to solve the issue of thermal comfort.[2]

Many studies have been conducted worldwide on the thermal comfort and the heat stress experienced by people in- and outdoors. More than 40 thermal comfort indices have been developed and applied, including WBGT (Wet Bulb Globe Temperature), WCT (Wind Chill Temperature), and DI (Discomfort Index). Recent additions are PMV (Predicted Mean Vote) and PET (Physiological Equivalent Temperature), which are used for statistical calculations on the human thermal sensation in an actual environment. The PMV (Predicted Mean Vote) index conceived by P. Ole Fanger is used to calculate the thermal load of the human body and to describe the extent of warm and cold sensations. The PMV is regarded as more sensitive than the other indices. For this study, we used the PMV index to measure thermal comfort, as the PMV considers both the microclimate components (temperature, humidity, air velocity, and mean radiant temperature) and the subjective features of an individual, such as metabolism and the amount of clothing worn. In general, the PMV range is between –3.5 and +3.5, while the comfort range is between –0.5 and +0.5. In addition to the thermal comfort indices, microclimate models, such as ENVI-met and Rayman, which can calculate and project the thermal comfort indices, have been developed and used [3,4]. However, simulation by a microclimate model cannot fully represent the complex urban spaces of the actual world. Consequently, verification is needed on the accuracy of the modeling results in comparison with the actual situation [5]. In South Korea, many researchers have studied the thermal environment using microclimate models, but the results obtained have not often been verified by comparison with data obtained from in-situ observations.

Therefore, this research aims to verify the accuracy of ENVI-met PMV, based on the on-site observation of PMV. Depending on whether the ENVI-met modelling results demonstrate adequate accuracy, our ultimate goal is to bring about and assess the thermal comfort of various places, using PMV gained from the ENVI-met microclimate modeling.

2. Methodology

2.1 Study area

This research was conducted at the pedestrian spaces and the square on the campus of the Changwon National University of South Korea(Fig. 1). The university is located at latitude 35°14'N and longitude 128° 41'E, in the south of the country. Although the target location was small, it was chosen for its diverse spatial properties, such as different paving materials, green spaces, shaded areas, and open spaces. In addition, it was convenient for mobile measurements and for applying an ENVI-met model, which simulates a small space.

Figure 1. Research location

Figure 2. Mobile measurement equipment

2.2 Research process

First, we consulted domestic and international studies on thermal comfort. We examined the theories of thermal comfort and the research methods relevant to in-situ measurements and microclimate simulation. Subsequently, we selected the research location, the spots for the mobile measurements, and the microclimate components were measured, which include temperature, humidity, air velocity, and the MRT, measured by the black-globe thermometer, needed to project PMV. Thereafter, operating the ENVI-met modeling on the same day, we compared the differences and the characteristics of each space. Finally, we analyzed the accuracy of the ENVI-met model, based on the in-situ measurements.

2.3 In-situ measurements

To calculate PMV, we performed mobile measurements of the microclimate from 08:00 to 17:00 on September 20, 2014 and from 10:00 to 16:00 on June 1, 2015. On September 20, 2014, the temperature was relatively too high for autumn in South Korea, and the thermal environment was considered unpleasant. The maximum temperature during the day was 27 °C and the weather was clear, with almost no clouds. On June 1, 2015, the start of summer in South Korea, the maximum temperature was 28 °C. We spent less than two hours on each mobile measurement. Because of the time differences in the mobile measurements between the measurements spots, it was necessary to adjust the measurements to take into account the time differences. We corrected the resultant values, using a correction formula in relation to the mobile measurements. We measured the microclimate components, such as temperature, humidity, air velocity, and the black-globe thermometer. The measurements were made at five-second intervals with Testo 480(Fig. 2), which was set up vertically and 1.2 m from the ground. The various paving materials, surrounding buildings, trees, and the shaded areas were considered in selecting the spots for the mobile measurements. We selected 27 spots on September 20, 2014 and 20 spots on June 1, 2015. We considered metabolism and clothing as individual variables to calculate PMV. Since the selected places were meant for pedestrians, we set the level of metabolism at 2.0met, which is usual for slow walking. Taking into account the weather on the day of measuring, we set the amount of clothing at 0.7clo, relevant to light tropical clothing.

2.4 Microclimate modeling

The ENVI-met model used for this research is a three-dimensional microclimate analysis program. Data f or this model, such as information on the buildings, paving materials, and vegetation are entered in a grid at the level of the urban canopy layer of an urban environment. The model can predict the distribution of the temperature, humidity, radiant energy, air current, and fluid flow at a micro scale. Two input data sets, i.e., an IN file (input file) and a CF file (main configuration file) are needed for an ENVI-met simulation. An IN file constructs the spatial properties of the target area, such as the geographical location, the mate rials and heights of the buildings, the types of vegetation, and the paving materials. For the purposes of o ur research, we set the size of the research area at 388m wide and 168m high, and the size of the grid at 2m. In addition, we entered the digitized information on the height of the buildings, pavement types, an d vegetation, using orthographic projection of aerial photographs. The CF file enters the initial meteorologic al values, such as the date and time of the measurement, temperature, humidity, and wind velocity. We e ntered the data as shown in Table 1. We used the 3.5 version of the ENVI-met model for the simulation, while the Leonardo 2014 program was used for the deduction and analysis of the data.

Table 1. 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
Ta (air temperature)	299.3 °K	300.5 °K
RH, Relative humidity	32%	53%
V, Wind velocity	1.6m/s at 10m height	0.9m/s at 10m height
Wind direction	West	West
Roughness Length Z0 at Reference point	0.1	0.1

3. Results and Discussion

3.1 The results of in-situ measurements

We set the basis for our analysis on the measurements taken at 13:00 and 15:00 on September 20, 2014 and at 12:00 and 14:00 on June 1, 2015. The in-situ measurements at 13:00 on September 20, 2014 for spot no. 27, which is close to buildings and has a grass pavement, indicated 4.8, the most unpleasant PMV level(Table 2). We presume that because spot no. 27 was close to the buildings, it was affected by both the radiant energy from the buildings and the radiant energy from the sun. In contrast, the PMV of spot no. 8 was 1.03, which is the most pleasant level. This area is paved with soil and shaded by buildings. At 15:00, spot no. 3 was the most unpleasant, and spot no. 6 was the most pleasant. Spot no. 3, an open space, did not have adequate shade compared with the other spots; therefore, we conjecture that its PMV value was caused by radiant energy from the sun.

As the measurements at 12:00 on June 1, 2015 indicate, spot no. 17, which has a grass pavement and is in direct sunlight, exhibited the most unpleasant level, while spot no. 6, which has a grass pavement and is shaded by trees, exhibited the most pleasant level(Table 3). We presume that as spot no. 17 is situated close to buildings, it was affected by both radiant energy from the sun and radiant energy from the buildings. Spot no. 9, with similar properties to those of spot no. 17, was affected by radiant energy from the nearby buildings. However, because of shade provided by trees, it was relatively more pleasant than was spot no. 17. Nevertheless, while the other shaded spots measured at the same time exhibited a PMV value of 2.5 on average, spot no. 9 exhibited a PMV value of 3.95, which is regarded as quite problematic. We surmise that this spot was affected more by the radiant energy from buildings than were the other spots. At 14:00, spot no. 18, paved with clay blocks and receiving direct sunlight, exhibited the highest value, while spot no. 6, paved with grass and shaded by both trees and buildings, was the most pleasant.

Table 2. PMV measurements on September 20, 2014, Type of shade

spot	Paving materials	13:00		15:00		spot	Paving materials	13:00		15:00	
		Type of shade	PMV	Type of shade	PMV			Type of shade	PMV	Type of shade	PMV
1	Asphalt	Building	1.29	Building	1.27	15	Clay block	x	3.73	x	2.82
2	Clay block	x	3.64	x	2.87	16	Asphalt	x	3.88	x	3.06
3	Clay block	x	3.29	x	3.94	17	Asphalt	Building	1.78	Building	1.04
4	Clay block	Tree	1.88	Tree	1.47	18	Clay block	x	3.24	x	2.38
5	Clay block	Building	1.32	Building	0.96	19	Clay block	x	4.19	x	2.81
6	Clay block	Building	1.19	Building	0.85	20	Wooden deck	x	3.85	Tree	1.34
7	Grass	Building	1.24	Building	0.96	21	Asphalt	x	4.33	x	2.67
8	Soil	Building	1.01	Building	1.03	22	Concrete	x	3.42	x	2.62
9	Grass	x	2.96	x	2.93	23	Grass	Tree	2.95	x	2.07
10	Soil	x	3.83	x	3.32	24	Clay block	x	3.95	Building	1.09
11	Grass	x	3.15	Tree	2.20	25	Clay block	x	3.75	x	1.90
12	Grass	x	3.61	x	3.26	26	Clay block	x	3.68	x	2.29
13	Urethane	x	4.06	x	3.77	27	Grass	x	4.80	x	2.52
14	Stone slab (gray)	x	3.75	x	2.38						

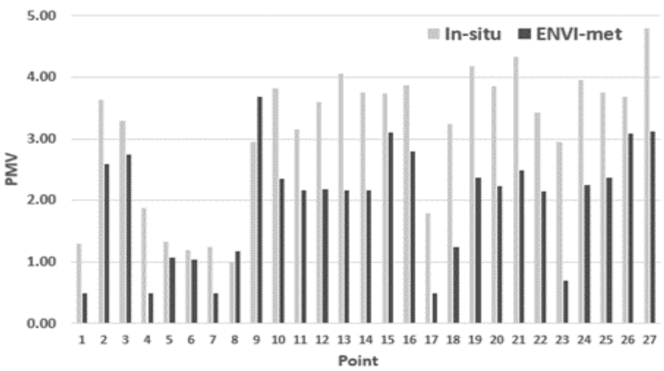
Table 3. PMV measurements on June 1, 2015, Type of shade

Spot	Paving materials	12:00		14:00		Spot	Paving materials	12:00		14:00	
		Type of shade	PMV	Type of shade	PMV			Type of shade	PMV	Type of shade	PMV
1	Asphalt	x	3.05	x	4.23	11	Wooden panel	x	4.25	x	4.52
2	Clay block	Tree	2.76	x	3.85	12	Grass	Tree	2.55	Tree	2.66
3	Clay block	x	3.69	x	3.80	13	Grass	x	4.24	x	3.84
4	Clay block	Tree	2.42	Tree	2.34	14	Urethane	x	4.17	x	4.68
5	Clay block	x	4.21	Building	2.46	15	Asphalt	x	4.41	x	4.16
6	Grass	Tree	2.26	Building & Tree	2.16	16	Asphalt	x	4.19	Building	2.45
7	Grass	x	3.68	x	3.64	17	Grass	x	4.76	x	4.17
8	Grass	x	2.97	x	4.40	18	Clay block	x	4.55	x	4.74
9	Grass	Tree	3.95	x	4.30	19	Asphalt	x	3.42	x	4.29
10	Clay block	x	3.84	x	4.05	20	Concrete	x	3.84	x	3.77

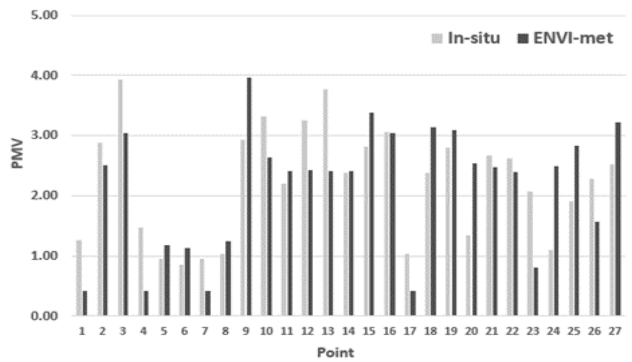
3.2 Results of ENVI-met, comparison of in-situ measurements, and analysis of their correlativity

From the ENVI-met output data, we extracted the temperature, humidity, wind velocity, and Mean Radiant Temperature, necessary for calculating PMV, in order to compare the in-situ measurements with the resul ts from the ENVI-met modeling. We compared the measurements conducted at 13:00 and at 15:00 on Se ptember 20, 2014, and the measurements conducted at 12:00 and 14:00 on June 1, 2015(Fig. 2). After c omparing the PMV value of the ENVI-met model and the PMV value of the in-situ measurements, we fou nd that relevant to the measurements at 13:00 on September 20, 2014, the PMV of the in-situ measurem ents was generally higher than was the PMV of the ENVI-met model. Verifying the accuracy, using a scatt er diagram distribution, indicated that in most cases the R^2 was 0.601(Fig. 3). Unlike the measurements at 13:00, the PMV at 15:00 exhibited similar values for both the in-situ measurements and the ENVI-met m odeling. However, large differences were found between some other pots, and the R^2 was 0.480. Therefor e, it appears that the measurements at 13:00 were slightly more accurate than were the measurements at

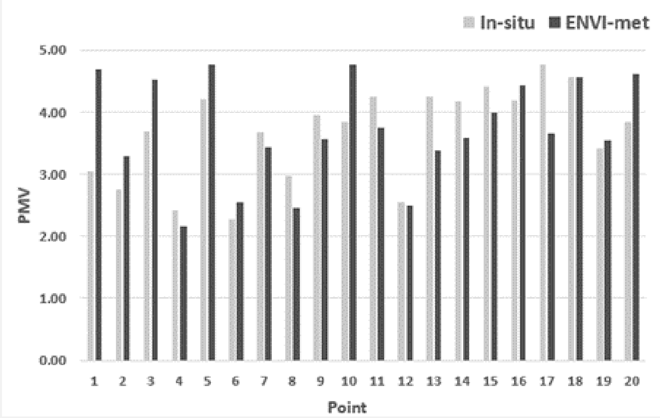
15:00. As regards the large difference between the values from the in-situ measurements and the values from the ENVI-met modeling, it is surmised that there were errors in the ranges of the shade provided by the trees and buildings, and the pixel size of the modeling did not produce an adequate resolution. On June 1, 2015, the R^2 value was 0.403 at 12:00 and 0.614 at 14:00. The measurements at 14:00 were more accurate than were the measurements at 12:00. As with the measurements on September 20, 2014, the measurements on June 1, 2015 tended to be similar at most of the spots. However, in relation to the trees, the range of shade and the degree of blocking the sun were dissimilar, depending on the height, water pipes, and the leaf size. The differences are attributed to the inability of the modeling to represent real situations exactly.



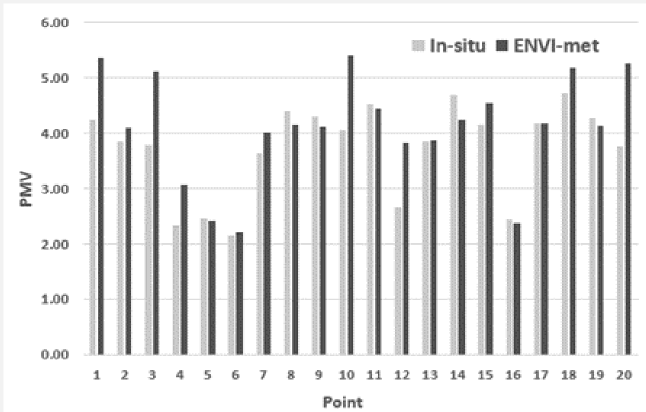
(a) *1p.m. on September 20*



(b) *3p.m. on September 20*



(c) *12p.m. on June 1*



(d) *2p.m. on June 1*

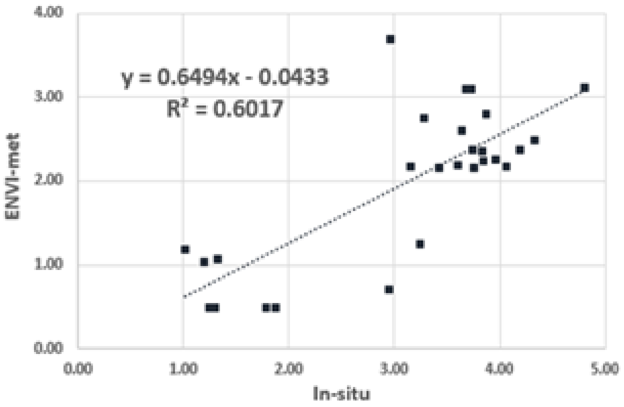
Figure 2 Comparison of between In-situ PMV and ENVI-met PMV on September 20, June 1,

4. Conclusions

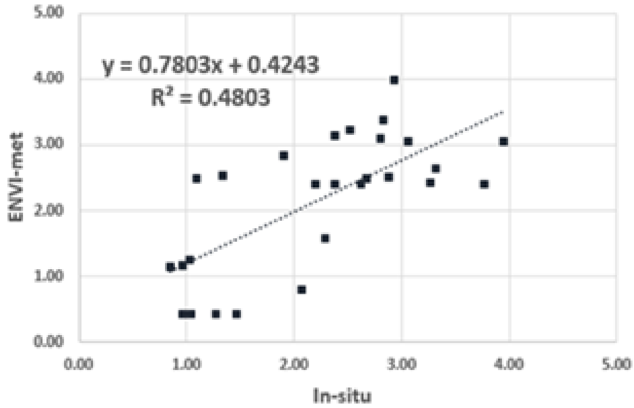
In this research, we performed in-situ measurements and ENVI-met modeling at the pedestrian paths on the university campus on September 20, 2014 and on June 1, 2015. We compared the thermal comfort in spaces with different properties, and verified the accuracy of the PMV of the in-situ measurements and the PMV of the ENVI-met modeling.

As regards the in-situ measurement, the PMV values differed, depending on the spatial properties. In summer, comfort largely depended on the presence or absence of sunlight. In particular, the shade provided by buildings resulted in more comfort than did the shade provided by trees. It appears that solar radiant energy is more effectively blocked by buildings than it is by trees. At the location directly exposed to radiant energy from the sun and situated near buildings, the level of thermal comfort was quite low in comparison with the other locations. This is attributable to the radiant energy from the sun, the buildings, and the surface of the earth. The results of a comparison of the PMV of ENVI-met and the PMV of the in-situ measurements show that the R^2 was 0.601 at 13:00 and 0.480 at 15:00 on September 20, 2014,while it was 0.403 at 12:00 and 0.614 at 14:00 on June 1, 2015.

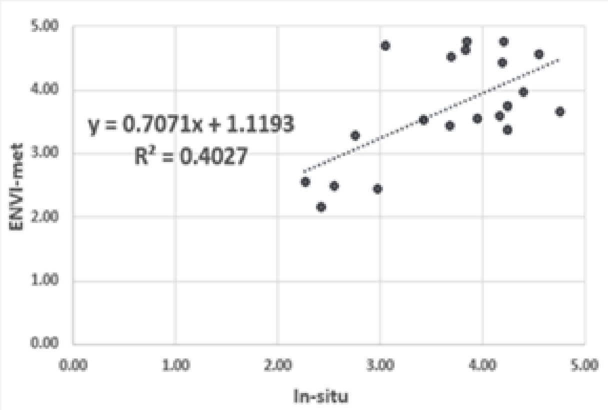
The results of modeling and the values from the in-situ measurement were mostly similar; however, at some specific spots, they were quite dissimilar. As urban areas have complicated and diverse spatial characteristics, modeling does not adequately represent the actual situations. In order to improve the accuracy of modeling, the paving materials, trees, and the building types of the target locations need to be studied in more detail and the information obtained have to be entered as data. If the accuracy of modeling is improved in future, it could be expected to more accurately predict the thermal comfort of various spatial conditions. ENVI-met can also be used to plan urban spaces that afford more comfort and to improve less comfortable spaces.



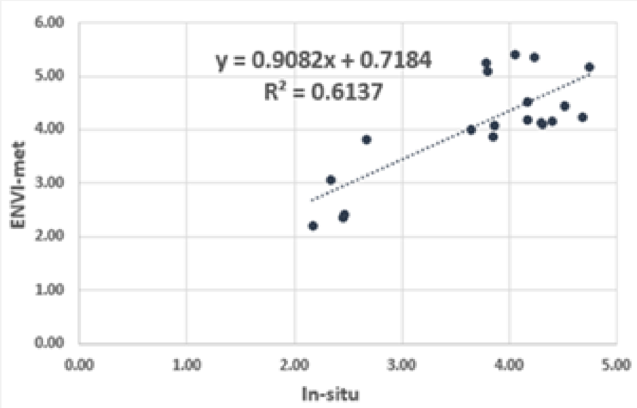
(a) 1p.m. on September 20



(b) 3p.m. on September 20



(c) 2p.m. on June 1



(d) 2p.m. on June 1

Figure 3. Scatter Plots of between In-situ PMV and ENVI-met PMV on September 20, June 1

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