COMPARISON OF MEASURED AND MODELLED MEAN RADIANT TEMPERATURE IN THE TROPICAL URBAN ENVIRONMENT

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ABSTRACT

RayMan is the most popular software package for thermal comfort research and urban planning. RayMan simulates the mean radiant temperature (T_{mrt}) and provides assessment of the human-biometeorology for urban areas. In this study T_{met} simulated by RayMan (version 1.2) has been validated with results from the six-directional radiation measurements in tropical urban settings in Malaysia. In addition, a validation of the physiologically equivalent temperature (PET) simulated by RayMan is conducted for the first time in the tropical context. T_{mrt} values from RayMan1.2 show some agreement with the measured values during middle of the validated days; however there was high fluctuation over that time due to rapid changes in radiation by cloud appearing. The results also show that RayMan1.2 considerably underestimated T_{mrt} during morning and evening. The simulated PET values followed the same pattern of the simulated T_{mrt} . However the simulated PET had a closer estimation to the experimentally obtained PET. The study also noted that RayMan1.2 accuracy seems to be site-related. Its simplification to the 3-D radiation environment led to variations in simulation accuracy depending on urban morphology. Therefore improvements of the RayMan software for simple and complex urban settings and tropical climates are required.

Keywords: : mean radiant temperature; six-directional radiation method; RayMan1.2 software; tropical urban environment.

1. INTRODUCTION

Consideration of human-biometeorology and thermal comfort for the assessment of urban areas has increased in recent years in response to different issues (Lee and Mayer, 2016, 2018a, 2018b; Lee, Mayer, and Chen, 2016; Lee, Mayer, and Schindler, 2014). First, the rates of world population living in cities are growing. In addition, urbanization has imposed significant changes to the natural ecosystem and landscape through the creation of largely impervious urban surfaces (Arnfield, 2003). Such changes to urban landscape have caused alteration in the local climate. The most obvious indicator of the alteration in urban climate is the increase in urban air and surface temperatures, a well known effect of Urban Heat Island (UHI) (Arnfield, 2003). Alteration in urban climate and the increase in urban air and surface temperatures are directly affecting outdoor comfort conditions, which can be worsened by climate change events (Changnon, Kunkel, and Reinke, 1996; You et al., 2017). The lack of effective urban planning and design can further exacerbate this situation (Ali-Toudert and Mayer, 2007; Johansson and Emmanuel, 2006; Thani, Mohamad, & Jamaludin, 2013). Hence, humanbiometeorological methods for the quantification of urban climatic impacts as well as to assess the effectiveness of adaptation and mitigation measures in improving outdoor conditions have become increasingly important (Ketterer and Matzarakis, 2014; Kuttler, 2011; Lee and Mayer, 2018a, 2018b; Lee et al., 2016; Wamsler, Brink, and Rivera, 2013).

For assessment of urban human-biometeorology and thermal comfort, detailed information of different parameters and processes governing micrometeorological conditions are required. These parameters and processes are often difficult to quantify in complex urban environments. Hence the use of numerical modelling has an advantage in which the involved parameters and processes are supplemented and enhanced with numerical calculations and simulations. A further advantage of numerical modelling is the ability to assess urban human-biometeorological and human thermal comfort conditions in relations to urban design and planning scenarios (Huang, Cedeño-Laurent, and Spengler, 2014; Lee and Mayer, 2018a, 2018b; Lee et al., 2016). However, modelling of microclimate often emerges with simplifications and limitations necessary to deal with the complexity of the urban environment (Ali-Toudert and Mayer, 2006; Thorsson, Lindberg, Eliasson, and Holmer, 2007).

The main feature for the modelling of microclimate is the determination of the 3D radiation fluxes for human beings and the calculation of the mean radiant temperature (T_{mrr}), one of the important parameters for the assessment of outdoor thermal comfort. Tmrt is the parameterization of the combined effect of short-and long-wave radiation fluxes absorbed by the human body. It is the basis of several human thermal indices, e.g., physiologically equivalent temperature (PET) (Höppe, 1999; H. Mayer and Höppe, 1987) and standard effective temperature (SET*) (Gagge, Fobelets, and Berglund, 1986). It is also considered the most spatially variable parameter compared to other parameters influencing thermal comfort. However, the issue of modelling the 3D radiation fluxes and formulas (Lee and Mayer, 2016; Naboni, Meloni, Coccolo, Kaempf, & Scartezzini, 2017). Thus, the modelling is not evident particularly in complex urban environments (Ali-Toudert and Mayer, 2006; Thorsson et al., 2007).

2. RAYMAN 1.2

RayMan1.2 is a spot-related software package used for the assessment of human bioclimate and outdoor thermal comfort (Matzarakis, Rutz, and Mayer, 2007, 2010). The inputs of the RayMan1.2 are meteorological data of air temperature, wind speed, water vapour pressure (relative humidity), global radiation and cloud cover, as well as inputs refer to urban morphology and others refer to features representative of a person. Furthermore, factors such as albedo, the Bowen ratio of the ground surface and turbidity of air can be adjusted in the RayMan1.2 software. Outputs of RayMan1.2 consist of the results of thermal indices for human-biometeorological conditions, as well as results of radiation fluxes and T_{mrt} . Also, with inputs of the geographical location and the temporal parameters, the RayMan1.2 software provides

possibilities to simulate sun paths in fish-eye view, as well as shadow patterns presented in grid-layout at period of the day.

The simulation tool of RayMan1.2 software is implemented with several features. For example T_{mrt} can be treated as part of the inputs when available. In addition, the RayMan1.2 can handle the simulation based on approximated input, such as input of Sky View Factor (SVF) in a form of fish-eye photo. As the RayMan1.2 takes vegetation and building morphology into account, the ability to evaluate human-biometeorological situation and further the assessment of applying adaptation and mitigation measures, such as urban replanning, street design, or different types of vegetation, is the main advantage of the software (Matzarakis et al., 2007). The RayMan 1.2 software is easy to use and has fast running time and free. These advantages are reflected in the increased popularity of the software in urban microclimate and outdoor thermal comfort research e.g. (Holst and Mayer, 2011; R. L. Hwang, Lin, and Matzarakis, 2011; Krüger, Minella, and Rasia, 2011; Ndetto and Matzarakis, 2017; Niu et al., 2015).

Several researchers validated the performance of RayMan by performing the validation of T_{mrt} based on field measurements (Andrade and Alcoforado, 2008; Chen, Lin, and Matzarakis, 2014; R.-L. Hwang, Lin, and Matzarakis, 2011; Krüger, Minella, & Matzarakis, 2014; Lee & Mayer, 2016; Lin, 2009; Matzarakis et al., 2007, 2010; Thorsson et al., 2007). The validations showed discrepancies in the validation results, where in some studies the RayMan simulation was found consistently underestimates T_{mrt} and in other studies the RayMan simulation tends to overestimate T_{mrt} . In general, RayMan showed a good performance particularly under relatively simple urban settings. Increasing complexity of urban settings and the modelling of conditions where the sun elevation is low would reduce the accuracy of RayMan.

Most of these validation studies however have been conducted in moderate to high latitude locations. This study therefore aims to examine RayMan1.2 in estimating the T_{mrt} in tropical urban settings of Malaysia when compared with the six-directional radiation method. The validation of the comfort index PET simulated by RayMan1.2 is also performed.

3. MEASURING SITES

Measurement were performed at the University campus in the National University of Malaysia, in Bangi, Malaysia (2°.54'N, 101°.47'E). Two different sites were selected for the measurements. The first site is a closed inner courtyard located near seven-story building and a parking lot with SVF value of 0.38 (Figure 1-a). The second site is a semi-open space with horizon limitations and SVF value of 0.79 (Figure 1-b).



Figure 1 (a, b): Photographs of the measurement sites (left) and fisheye images (right) generated by RayMan1.2.

3.1 Measurements and Methods

Micrometeorological station and Measurements

The micrometeorological station shown in Figure 1(a, b) was equipped with instruments as defined in Table 1. This includes sensors to measure air temperature, relative humidity, and wind speed. Three net-radiometers, each consists of two pyranometers and two pyrgeometers, were set up on the station to measure the six-directional short and long-wave radiation fluxes. All instruments were fixed at a height of 1.1m a.g.l representing the height of the weighting center of a standing person (Thorsson et al., 2007). The recording interval was set to 1-min.

Table 1: Measured parameters and instruments		
Quantity	Instrument	Accuracy & range
Air temperature, Ta		0.15°C - 0.35°C
	Skye inst.	(-40 to +80°C)
Relative humidity,	rht+ PT100 sensor	Better than +2% RH
RH		(0-100 %)
	Delta OHM: AP3203	± 0.05 m/s (0.05-1 m/s)
Wind speed, Va	omnidirectional hot-	$\pm 0.15 \text{ m/s} (1-5 \text{ m/s})$
_	wire	
Short- and long-	Delta OHM: LP NET	Pyranometers: 0-2000 W/m ²
wave radiation	14	Spectral range: 335 nm ÷ 2200 nm
fluxes, K, L	2 pyranometers,	(95%)
	2 pyrgeometers	Pyrgeometers: $-300 - +300 \text{ W/m}^2$
	temperature sensor	Spectral range: 5.5 µm ÷ 45 µm
	(NTC), and thermopiles	Working temperature: -40 °C - 80 °C

A total of three days of measurements were carried out at the sites: on 14 February 2017 at the site 1 and on 20 August 2017 and 25 February 2018 at the site 2. The measurements were recorded on each day from 8:00 to 21:00. The weather during the days brought hot, humid conditions with intense solar radiation and occasional cloudy skies. The average air temperature at the measured days was between 29.6 and 31.4°C and the average RH was between 55 and 60%. The average wind speed was < 1.8m/s. The average global radiation was between 450 and 550 W/m² and the highest recorded global radiation was 1160 W/m². These conditions are representative of the local tropical climate in Malaysia where there is no distinct seasons.

The six-directional method to calculate T_{mrt} and PET

An accurate determination of T_{mrt} is very difficult and mostly impossible in complex urban settings because this requires measurements of all shortand long-wave fluxes along with angle factors between a person and the surrounding. An alternative way to T_{mrt} is by limiting the measurements of radiation fluxes to only the six perpendicular directions surrounding a person, i.e., from four lateral directions, upwards and downwards (Holst and Mayer, 2011; Kántor, Kovács, and Lin, 2015; Lee, Holst, and Mayer, 2013; Helmut Mayer, Holst, Dostal, Imbery, & Schindler, 2008; Thorsson et al., 2007). To date this method is the most reliable measuring method to determine T_{mrt} (Kántor et al., 2015; Kántor, Lin, & Matzarakis, 2014; Lee et al., 2016). The six individual measurements of short-wave radiation fluxes Ki and long-wave radiation fluxes Li multiplied by the angle factors Fi between a person and the surrounding (i=1-6) are used to calculate the T_{mrt} following the Stefan-Boltzmann law in equation [1] (Thorsson et al., 2007):

$$T_{mrt} = \sqrt[4]{\frac{\alpha_k \sum_{i=1}^6 K_i F_i + \alpha_l \sum_{i=1}^6 L_i F_i}{\alpha_l \sigma} - 273.15}$$
[1]

Where σ is the Stefan–Boltzmann constant (5.67×10⁻⁸ Wm⁻² K⁻⁴), α_k , α_l are the absorption coefficients for short-wave fluxes (standard values is 0.7) and long-wave fluxes (standard values is 0.97). To calculate T_{mrt} for a standing person, Fi is set to 0.22 for radiation fluxes from the lateral directions and 0.06 for upwards and downwards radiation fluxes (Thorsson et al., 2007).

The results of T_{mrt} by the six-directional method (T_{mrt} (rad.)) along with the meteorological data of air temperature, wind speed and water vapour pressure were used to determine the experimentally obtained PET.

Application of RayMan1.2 to simulate T_{mrt} and PET

The meteorological data of air temperature, wind speed, water vapour pressure (relative humidity), global radiation and cloud cover were used as inputs in RayMan1.2 to simulate T_{mrt} and PET. The default values of the albedo, Bowen ratio and the ratio of diffuse and global radiation have been used. An input of the urban structures of the sites has been considered in RayMan1.2. The simulation results of Tmrt and PET were validated by comparison with the experimentally obtained results.

4. RESULTS AND DISCUSSION

Validation of the simulated T_{mrt} by RayMan1.2

As shown in Figure 2, the variations in T_{mnt} values during the middle of the measuring days can be explained by rapid changes in weather conditions from clear to cloudy conditions. The maximum values of the measured T_{mnt} were between 70-75°C. The simulated Tmrt followed the same patterns over that time but with more fluctuation with maximum values between 75-80°C. In morning and afternoon when the sun elevations were low, RayMan 1.2 software considerably underestimated T_{mnt} to about 10°C in all the three days. By adjusting the default Bowen-ratio, albedo and the ratio of diffuse and

UNIVERSITI PUTRA MALAYSIA 38 Alam Cipta Vol 12 (Special Issue 1) Sept 2019: Energising Green Building global radiation for the local context, the RayMan 1.2 still underestimated T_{mrt} in morning and evening but drastically overestimated it during middle of the measuring days. Thorsson et al. (2007) reported similar results based on measurements and simulations done in the high latitude city of Göteborg, Sweden. Both reflected and diffused short-wave fluxes as well as the emittance of long-wave fluxes from the surrounding surfaces are important for the estimation of T_{mrt} . The formulation used by the RayMan to simulate the 3D radiation fluxes are simplified and does not consider the horizon (Lee and Mayer, 2016). These aspects should be considered for the determination of T_{mrt} .





Figure 2 (a-c): Tmrt as calculated by six directional radiation method and the simulated T_{mrt} by RayMan1.2: (a) at the site 1; (b, c) at the site 2.

As shown in Figure 3 a-c the simulated and measured T_{mrt} values were strongly correlated, with R² values ranging between 0.95 and 0.97. It is evidence that the RayMan1.2 tends to underestimate T_{mrt} at lower ranges of Tmrt values, and overestimated it at higher ranges of T_{mrt} values. The magnitude of the T_{mrt} underestimation was higher than that of its overestimation particularly in site 2. Also in all three days the RayMan1.2gives a scatter in T_{mrt}. The scatter is increasing at higher ranges of T_{mrt}, i.e., at the middle of the days, which can be interpreted by rapid change in radiation fluxes by cloud appearing.

Furthermore, Figure 3 a-c indicates two differentiated systematic errors in the regressions between simulated and measured T_{mrt} . The simulation results show systematically lower T_{mrt} values at the site 2 compared to the site 1. Probably, the differentiated systematic errors reveal that the accuracy of RayMan1.2 is influenced by urban morphology and SVF. Since the modification of the 3D radiative fluxes (shortwave reflected radiation and longwave radiation) is highly correlated with SVF (Andrade and Alcoforado, 2008), the simplification to these aspects may result in such differences in the accuracy of RayMan1.2.

Therefore, RayMan needs to be improved to consider the radiative fluxes for applications in simple and complex urban settings. Furthermore, the quantification of clouds in urban areas and the turbidity estimation need to be enhanced. Improvement of atmospheric turbidity for tropical environments is also important.





Figure 3 (a-c): T_{mrt} as calculated by six directional radiation measurements vs. simulated by RayMan1.2: (a) at the site 1; (b, c) at the site 2.

Investigation of the effect of simulated $T_{\rm mrt}$ on thermo-physiological assessment.

The simulated results of PET by RayMan1.2 were validated by comparison with those obtained by experimental procedures. As shown in Figure 4, the scatter and systematic error in the regressions between simulated and measured PET followed the same pattern as the T_{mrt} . This was expected because T_{mrt} is the main factor affecting PET in outdoor environments. Nevertheless the simulated PET by RayMan1.2 is less affected by inaccuracy of the simulated T $_{mrt}$. The R² values ranging between 0.96 and 0.98 indicate stronger correlations between simulated and experimentally obtained PET. Also the simulated PET values particularly when high ranges of T_{mrt} values occurred. The modification in the radiative fluxes has less effect on PET because the thermo-physiological index is also depending on other thermal comfort factors; namely, air temperature, water vapour pressure, air speed, human clothing and activity. Increasing the accuracy of the simulation of PET index requires accurate estimates of all these factors including T_{mrt} .



Figure 4 (a-c): PET as calculated by experimental data vs. simulated by RayMan 1.2: (a) at the site 1; (b, c) at the site 2.

5. CONCLUSION

In this study the RayMan1.2 software was validated by comparison with field measurements for the tropical outdoor urban environment. As the T_{mrt} can be determined by field measurements and modelling, the consistency between measured and simulated T_{mrt} was utilized as a criterion for the validation of the RayMan1.2 software. The simulated T_{mrt} results by the RayMan1.2 software were compared with the six-directional radiation method as a reference method. The results are for three day at two different sites in a tropical urban environment.

The study shows that RayMan1.2 software gives reasonable results during the middle of the day. However, in morning and late afternoon the RayMan1.2 drastically underestimates T_{mrt} data. The study also shows that the software simulation of different urban settings leads to different systematic errors depending on the urban morphology and SVF. The reflected and diffused short-wave fluxes as well as the long-wave fluxes from the surrounding surfaces, which are highly correlated with urban morphology, are simplified by RayMan1.2 (Lee and Mayer, 2016 ; Naboni et al., 2017). The results suggest that the accuracy of RayMan1.2 may be dependent on SVF, i.e., the simulation for spaces with different SVFs may achieve different levels of accuracy.

The effect of the simulated T_{mat} on the thermo-physiological index PET is also analyzed. The index has been chosen for validation because it has been employed in several studies of outdoor thermal comfort. The simulated PET values from RayMan1.2 software followed the same pattern of the simulated T_{mrt} . Nevertheless the simulated PET values have a closer estimation to the experimentally obtained PET. In addition, the RayMan1.2 gives slightly less scatter in PET in comparison to Tmrt.

Therefore, based on the results of the validation, improvements to the RayMan1.2 simulation for the short- and long-wave radiant flux densities from the surrounding 3D environment is required. Moreover, there are some other parameters whose assessments have to be improved; e.g. the quantification of the clouds and atmospheric turbidity.

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