Comparison of Measured and Modelled Mean Radiant Temperature in the Tropical Urban Environment

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Abstract— **Mean radiant temperature (Tmrt) is the most influential parameter governing heat stress and outdoor thermal comfort. It integrates the effect of all short- and long-wave radiation fluxes received by the human body. The most accurate way to determine Tmrt is by six-directional radiation measurements. The method is complex and expensive, as it requires combination of pyranometers and pyrgeometers for measuring the short- and long-wave radiation fluxes received by a person from the six perpendicular surroundings. RayMan is one of the most popular models for thermal comfort research and urban planning. The model calculates Tmrt and also provides assessment of the thermal bioclimate for urban areas with the use of basic metrological information, such as global radiation, air temperature and wind speed. In this study validation of RayMan1.2 simulation was reported with results obtained from the six-directional method in the tropical urban setting in Bangi, Malaysia. Tmrt values from RayMan show some agreement with the measured values during middle of the day; however there was high discrepancy over that time caused by rapid changes in radiation by cloud appearing. During morning and evening, i.e., at low sun elevations, the model considerably underestimated Tmrt. This can be due to low estimation of short- and long-wave radiation fluxes from the surrounding surfaces. The model simplifications to the diffused and reflected short-wave fluxes as well as the emittance of long-wave radiation fluxes from the 3D surrounding emerge in such differences between modelled and measured Tmrt. Also the limited quantification of clouds and the atmospheric turbidity impact the applicability of the model for the tropics. Therefore improvements of the RayMan model for tropical climates and complex urban structures are required.**

Keywords— mean radiant temperature; six-directional radiation method; RayMan model; tropical urban environment.

I. INTRODUCTION

Radiation heat has the most dominant effect on human energy balance and thermal comfort in outdoor environments mainly during sunny conditions. To parameterize the effect of radiation in the human energy balance, the Mean Radiant Temperature "Tmrt" has been introduced which integrates the effect of all short- and long wave radiation fluxes reaching the body into a single temperature-unit value [1]. Tmrt is defined as the uniform temperature of a hypothetical spherical surface surrounding the subject (emissivity ε=1) that would result in the same net radiation energy exchange with the subject as the actual, complex radiative environment. The latter usually exists in urban environments which experience greater variability and asymmetry of direct and diffuse short-wave fluxes as well as the long-wave fluxes originating from the surrounding urban surfaces [2], [3]. Also radiation fluxes and the resulting Tmrt are the most spatially variable parameters in urban areas as compared to other parameters like air temperature and humidity. Finally, Tmrt is the most important parameter for human bio-meteorological assessment through thermal indices, such as predicted mean vote (PMV), physiologically equivalent temperature (PET) and standard effective temperature (SET*).

II. CALCULATION OF THE MEAN RADIANT TEMPERATURE

An accurate determination of Tmrt is very difficult and mostly impossible in complex urban environments because this requires measurements of all short-and long-wave fluxes along with angle factors between a person and the surrounding. An alternative way to Tmrt is by limiting the measurements of radiation fluxes to only from the six perpendicular directions surrounding a person, i.e., from four lateral directions, upwards and downwards, with the use of six pyranometers and six pyrgeometers or three net-radiometers [4], [5]. The integral radiation measurements weighted by the angle factors Fi can be used to calculate the Tmrt Following the Stefan–Boltzmann law [5]:

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

Where σ is the Stefan–Boltzmann constant (5.67×10^{-8} $Wm^{-2} K^{-4}$), and α_k, α_l are the absorption coefficients for short-wave radiation (standard values is 0.7) and long-wave radiation (standard values is 0.97). To represent the absorbed radiation by a standing person it is sufficient to set Fi = 0.22 for radiation fluxes from the lateral directions and 0.06 for upwards and downwards radiation fluxes [5].

To date the six-directional method is the most reliable method to estimate Tmrt [6]. It was used in a number of studies e.g. [7]–[10] and considered the most suitable for analyzing the impact of urban form on the variability of Tmrt [11], [12]. However it has disadvantage in terms of complexity and may be cost prohibitive. This has increased the demands for numerical modelling or applying measuring techniques with some assumptions and simplifications such as, globe thermometer [1]. Several models have been developed to simulate the radiation environment and estimate the Tmrt in outdoor urban settings. The most models used to modelling the radiation environment are RayMan [2], ENVI-met [13] and SOLWEIG [14]. Recent models have been proposed, CityComfort+ [15] and CitySim can be used to predict radiation environment in complex urban structure [16]. However, the important issue of the modelling of radiation environment is that the climate model are often simplified by assuming several parameterizations and limitations [3]. Therefore, the validation of models' simulations is necessary as the models have become increasingly important tools for urban climate and thermal comfort researches.

III. THE RAYMAN MODEL

RayMan is the most common model used to determine Tmrt [2], [17]. The model requires basic meteorological parameters, such as air temperature, air humidity, cloud cover, etc. The model takes complex urban structures into account, which is suitable for several applications in urban areas such as urban planning and street design [2]. The main advantage of the model is that it can be used to analyze climatic conditions and evaluate human bio-meteorological situation with the use thermal indices PMV, PET and SET*. However, the model can only assess Tmrt and thermal indices for a one-point one-time context.

With inputs of the geographical location and the temporal parameters (date of the year and time of the day) the model provides possibilities to show sun paths in fish-eye view (Fig.1), as well as shadow patterns presented in grid-layout at period of the day. Another advantage is easy to use and has fast running time and it is free. These advantages make the model most popular with lots of already existing studies used the model to evaluate urban environmental conditions and thermal comfort, e.g. [18]–[20].

Several studies validated the accuracy of Tmrt values simulated by RayMan model [2], [10], [18], [17], [21]–[24]. The validations show discrepancies in the simulations of Tmrt, where in some studies the model was found consistently underestimates Tmrt and in other studies the model tends to overestimate Tmrt. However, it must be mentioned that the validation procedures and the results in these studies were comparatively inconsistent due to differences in terms of climate, applied methods and spatial and temporal scales.

So far no studies have validated the accuracy of the RayMan model for the tropical urban environments in Malaysia. Therefore the aim of this study is to examine Rayman model in estimating the Tmrt in tropical outdoor urban setting of Malaysia when compared with the six-directional radiation measurements. A validation of the resulted PET by RayMan is also performed to analyze the effect of Tmrt simulation on the human-biometeorological assessment.

IV. MEASUREMENTS AND METHOD

The meteorological measurements were conducted in the University campus in the National University of Malaysia, Bangi, Malaysia (2º.55'N, 101º.46'E). The measuring site is located at a semi-open space surrounded by buildings with Sky View Factor (SVF) of 0.79 (Fig.1). The measurements were conducted on 20 August 2017 from 8:00 to 21:00 local time. The one-day time period can be considered representative of a tropical climate in Malaysia. The weather during the day brought hot, humid conditions under clear to cloudy sky. The maximum air temperature was 34ºC, with daily averages of 29.7ºC and wind speed of 1.29 m/s.

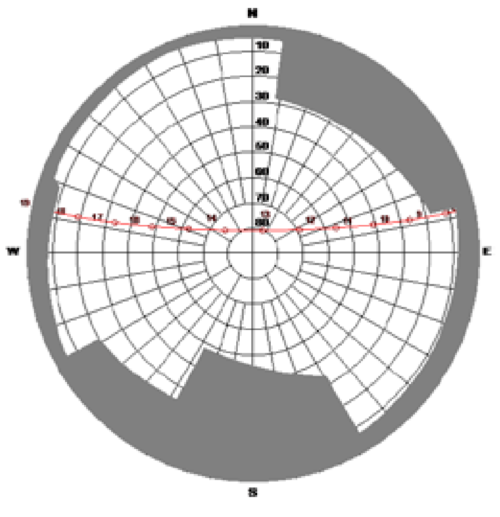

Fig. 1. An illustration of the fish-eye view and sun duration at the measuring site as simulated by RayMan

The short- and long-wave radiation fluxes densities were measured from the six-directional surroundings, i.e., from the lateral four directions, upwards and downwards. Air temperature, air velocity and relative humidity were measured simultaneously at the measuring site. The measurement height was 1.1m above the ground [6]. The recording interval was set to 1-min-averages for all parameters. The measurements of radiation flux densities and the determination of angle factors for a standing person were used to obtain Tmrt according to equation (1). The results of Tmrt along with the measured meteorological parameters were used to determine the thermal index PET which corresponds to comfort level of a pedestrian.

The simulation of RayMan was implemented using input parameters of air temperature, air velocity, humidity, cloud cover and global radiation. The obstacles of buildings surrounding the measuring site were taken into account in the model. The simulation of the model was as the same time resolution as the experimental measurements. The simulation results of Tmrt and PET were validated by comparison with those obtained Tmrt and PET values by experimental measurements.

V. RESULTS AND DISCUSSION

A. Validation of Tmrt simulated by the RayMan1.2 in a relatively complex urban environment

The six-direction radiation method was used to obtain the reference mean radiant temperature, Tmrt (rad.) for a standing person. The obtained basic microclimatic data were used as inputs for RayMan to simulate Tmrt.

As shown in Fig.2, the high variation in short-wave radiation fluxes and the resulting Tmrt can be explained by rapid changes in weather conditions from clear to cloudy conditions. This resulted in a sharp fluctuation in Tmrt with a maximum value of 70ºC during the middle of the day. The modelled Tmrt using RayMan 1.2 followed the same pattern but with more fluctuation over that time. Its maximum value of 75ºC was simulated at the same time the maximum Tmrt occurred. In the morning and afternoon when the sun elevation was low the RayMan model drastically underestimated Tmrt with differences of about 10ºC. By adjusting the default Bowen-ratio, albedo and the ratio of diffuse and global radiation for the local context, the model still underestimated Tmrt in morning and evening but considerably overestimated it during the middle of the day.

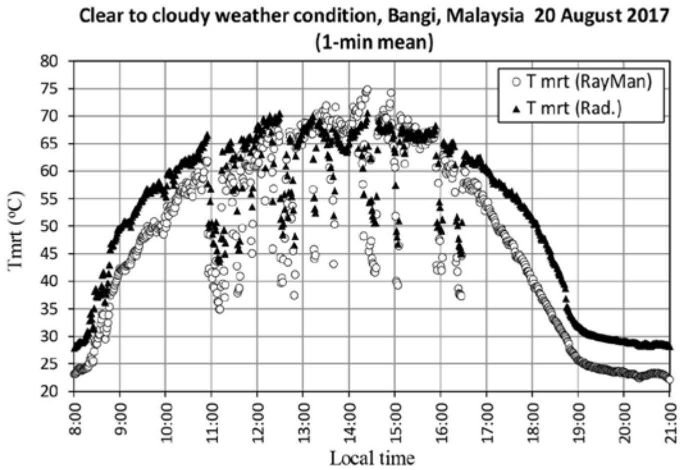

Fig. 2. Tmrt as calculated by six directional radiation method and the simulated Tmrt by RayMan1.2 software.

Thorsson et al. (2007) [6] reported similar results based on measurements and simulations done in the high latitude city of Göteborg, Sweden. It is obvious that the model gives a better approximation of Tmrt when the sun elevation was high, but at low solar elevations the model underestimates Tmrt. Both reflected and diffused short-wave fluxes as well as the emittance of long-wave fluxes from the surrounding surfaces are crucial for the estimation of Tmrt. It is not clearly described by Matzarakis et al. (2010) [17] how they are simulated and whether multiple reflections and emittance of radiation flux densities are considered [24]. According to Lee and Mayer (2016) [24], the formulation used by the model to simulate short-wave radiant fluxes from the upper half space does not consider the horizon and cloudiness. In addition, the atmospheric turbidity is taken into account using tabular data, rather than site-related data [24], [25].

Fig. 3 shows Tmrt as calculated by six directional radiation measurements vs. simulated by RayMan software. The model gives a slight scatter in Tmrt values. The scatter is increasing at high ranges of Tmrt values, i.e., during the middle of the day, but at the same time the simulated Tmrt values are closer to the experimentally obtained Tmrt. The linear relationship between both variables has an R^2 = 0.958 and the linear regression shows systematic errors between simulated and experimentally obtained Tmrt at low ranges of Tmrt. This points out to the main disadvantage of the model, where the model's simulations underestimated Tmrt for morning and evening periods as compared to Tmrt calculations by the six-directional method. On-site measurements are therefore necessary to evaluate the performance of the simulations through comparison between predicted and measured results.

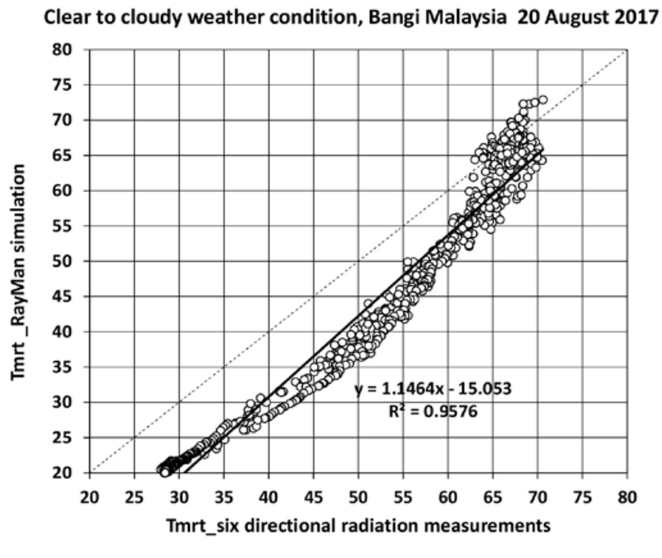

Fig. 3. Tmrt as calculated by six directional radiation measurements vs. simulated by RayMan 1.2 software.

B. Investigate the effect the simulated Tmrt values on the thermo-physiological assessment

Tmrt is an important parameter in the human heat budget and its derivative thermo-physiological assessment indices. The RayMan model can simulate thermal indices such as

PMV, PET. In this study the simulated PET index by RayMan was validated against the determined PET from measurements. As shown in Fig. 3, the values of PET simulated by the RayMan are affected by of the accuracy of Tmrt values. This was expected because Tmrt is the main factor affecting PET during sunny conditions. Nevertheless there is less systematic error in the simulated PET as compared to the Tmrt variables and the R^2 value (0.961) points to a slightly higher correlation between PET variables. Also the simulated PET has a closer approximation to PET when high ranges of Tmrt values occurred, i.e., at high sun elevation.

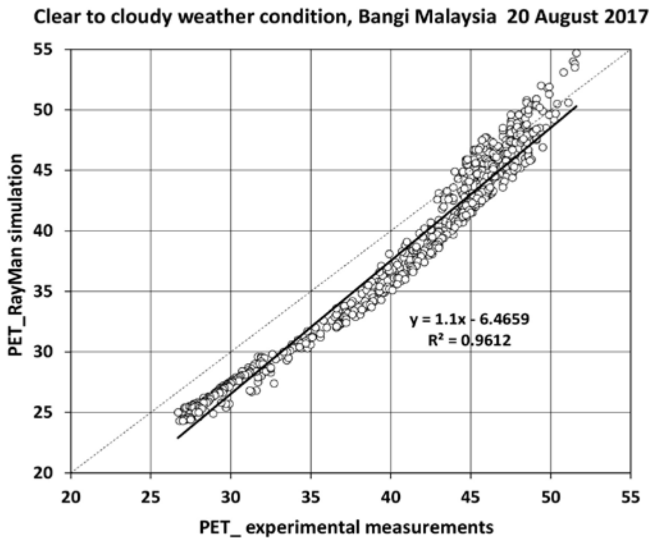

Fig. 4. PET as calculated by experimental measuremtns vs. simulated by RayMan 1.2 software.

VI. CONCLUSION

In this case study the estimated Tmrt results by the RayMan simulation were compared with six directional radiation measurements as a reference method. The results are only for one day, but they identify and explain important differences between the six-direction radiation method and RayMan model under tropical urban environment.

The study showed that, in tropical outdoor urban setting, the RayMan model's simulation gives reasonable results during the middle of the day. However, in morning and late afternoon the difference between Tmrt data from the two methods became drastically high. The error in the modelling Tmrt increased during morning and evening. This points out to the main disadvantage of the model, when both reflected and diffused short-wave fluxes as well as the emitted long-wave fluxes from the surrounding surfaces increased.

The effect of the simulated Tmrt on the thermo-physiological index PET is also analyzed. The simulated PET values from RayMan model followed the same pattern of the simulated Tmrt. Nevertheless the simulated PET values had a closer estimation to the obtained PET by experimental measurements. In addition, the model gives slightly less scatter in PET in comparison to Tmrt particularly at lower ranges.

Therefore, based on the results of the validation, it is important to improve the RayMan simulation of short- and long-wave radiant flux densities from the surrounding 3D environment. In addition, the quantification of the atmospheric turbidity and cloud cover needs further improvement for the applicability in the tropics.

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