Building and Environment 64 (2013) 118–129

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Outdoor mean radiant temperature estimation in the tropical urban environment

Chun Liang Tan [a,*], Nyuk Hien Wong [a], Steve Kardinal Jusuf [b]

[a] Department of Building, National University of Singapore, 4 Architecture Drive, Singapore 117566, Singapore
[b] Centre for Sustainable Asian Cities, National University of Singapore, Singapore

ARTICLE INFO

Article history:
Received 5 January 2013
Received in revised form
18 March 2013
Accepted 20 March 2013

Keywords:
Outdoor thermal comfort
Mean radiant temperature
Customised globe thermometer
Sky view factor
Urban greenery

ABSTRACT

A large scale estimation of mean radiant temperature (t_{mrt}) is conducted at two sites using customised globe thermometers. The measurement points cover a variety of urban typologies such as high-rise offices, parks, large water bodies and housing apartments. Data is derived using a t_{mrt} formula calibrated to the local climate. Measurements for clear, sunny days are used for the analysis of the average diurnal t_{mrt} profile.

The diurnal t_{mrt} profile shows that the t_{mrt} differential between points is most evident during daytime, and is affected most significantly by shade cast by trees and buildings. Results also show that common urban constituents such as greenery and large water bodies, while proven to effectively reduce the ambient temperature of its surroundings throughout the day, do not affect t_{mrt} significantly after nightfall. Further analysis reveals a correlation between sky view factor and t_{mrt} in the day. Measurement points in different parks exhibit contrasting trends in t_{mrt} reduction.

Results of the study also provide a realistic threshold for the lowering of outdoor t_{mrt}. Trees, shrubs and green walls may be introduced into the outdoor environment with the intention of reducing t_{mrt} to a desirable level for a specific time range.

1. Introduction

Modern civilisation has improved our lives in many ways. It has also produced a new environment, creating issues of adaptation. These issues include global warming, industrial waste, and pollution. More people are vulnerable to urbanisation problems as the ever increasing urban population, which was estimated at 48% or three billion, is expected to be five billion by 2030 [1]. The projected global average surface warming at the end of the 21st century is between the range of 0.3 °C–6.5 °C [2]. The rise in temperature will have a direct impact on the quality of outdoor spaces in urbanised areas.

Outdoor spaces are important as it encompasses pedestrian traffic as well as various outdoor activities. Increased outdoor activity in urbanised areas can generate many positive attributes [3,4]. Therefore, it is important for outdoor spaces to be properly designed. The outdoor microclimate is an important factor that determines the quality of outdoor urban spaces as it affects thermal comfort and subsequent usage [5].

There are several methods of determining the quality of both the indoor [6,7] and outdoor [8] microclimate. The use of biometeorological indices has enabled quantification of thermal comfort and assessment in tandem with behavioural aspects. Useful heat stress indices have also been developed to describe thermal stress [9–11]. According to the rational approach [10], the evaluation of thermal environments by means of a suitable comfort [6] or stress index [9,10] requires the measurement of four physical quantities of the air temperature, the mean radiant temperature, the air velocity and the relative humidity. Among them, one of the main factors contributing to the thermal response of man to his surrounding environment is the mean radiant temperature (t_{mrt}). This quantity plays a crucial role not only in indoor situations but also outdoors as indicated in several studies which have stressed that outdoor thermal comfort is highly dependent on the short wave and long wave radiation fluxes from the surroundings [12,13].The estimation of t_{mrt} can be done by two-sphere radiometers, globe thermometers, constant-air-temperature sensors [14]. Calculation of t_{mrt} is also possible using radiant fluxes and the angle factors of surrounding surfaces [14,15].

* Corresponding author. Tel.: +65 6516 4691.
E-mail addresses: tcl@nus.edu.sg, terrencefishtan@gmail.com (C.L. Tan), bdgwnh@nus.edu.sg (N.H. Wong), stevekj@nus.edu.sg (S.K. Jusuf).

0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.03.012

The effects of t_{mrt} can be studied through numerical modelling [16,17]. This method is useful when used for iterative studies such as the comparison of width-to-height ratios and orientations of street canyons. However, model geometry and ambient conditions are often simplified. Recent developments in solar and long wave environmental irradiance modelling takes into account large-scale urban geometry as well as important urban components such as tree and shrubs [18].

The estimation of radiant temperature is often an integral component to the assessment of thermal environments. Common thermal assessment indices such as the Physiological Equivalent Temperature (PET) and the recently developed Universal Thermal Climate Index (UTCI) are evaluated with t_{mrt} as a variable component [19–21]. Other heat stress indices such as the Wet Bulb Globe Temperature (WBGT) consider radiant temperature in the form of the globe surface temperature [22,23]. The fluctuating radiation fluxes due to complex environments have contributed to the uncertainty in t_{mrt} estimation, and studies have shown that it can affect the overall thermal assessment in some temperature ranges [24]. Therefore, it is important that the estimated t_{mrt} can accurately reflect the prevalent conditions of radiation fluxes of the measured space.

The urban environment can be described as an amalgamation of buildings, vegetation, water bodies and many other constituents. It is therefore important for us to understand how the behaviour of t_{mrt} is influenced by these factors in the outdoor urban environment.

The purpose of this study is to observe the diurnal t_{mrt} profile of the outdoor environment and to identify any relation between t_{mrt} and the corresponding urban typology.

2. Methodology

2.1. Calibration of customised globe thermometers

Customised globe thermometers are used to estimate the t_{mrt} for all measurement points. In order to ensure the accuracy of t_{mrt} estimation, readings from the customised globe thermometers are first estimated against readings from a net radiometer. The mean convection coefficient of the formula used for t_{mrt} estimation is recalibrated for use in the local context.

The mean radiant temperature is defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure' [25]. It is one of the meteorological parameters governing human energy balance and human thermal comfort.

The measurement of t_{mrt} is done via the use of a globe thermometer [26–29]. The globe thermometer was first developed for indoor measurements, but has later been applied outdoors [30]. The Vernon globe is a 150 mm diameter copper sphere painted black with a thermometer positioned in the middle of the sphere. For convenience, smaller globes were developed. The 38 mm globe thermometer is a common option as the globe used is a table tennis ball, which can be readily purchased and conveniently replaced [31]. The accuracy of the 38 mm globe thermometer can be adjusted to cater to outdoor conditions by recalibrating the mean convection coefficient. This method has been tested in Sweden [32] and shown to be effective in outdoor conditions.

To ensure validity of the t_{mrt} estimation for this study, the mean convection coefficient of the formula for t_{mrt} estimation is recalibrated. This is done by comparing the estimates from the customised globe thermometer to the long wave and short wave readings from a net radiometer.

Two sets of measurements are made, one at each of the study areas (Table 1).

Two different methods for measuring the t_{mrt} outdoors are put to comparison:

1. Method A – Radiant flux measurements, where t_{mrt} calculation is based on short wave and long wave angular factors for a sphere;
2. Method B – 40 mm flat grey globe thermometer with t_{mrt} equation from ISO 7726:1998 [14].

Results are used to recalibrate the t_{mrt} formula for Method B, so that the mean convection coefficient in the t_{mrt} equation will be representative of local outdoor conditions. Recalibration is done via statistical analysis using the IBM SPSS software [33].

Measurements are then made in another area with Methods A and B. The t_{mrt} formula used for the second measurement will be with the recalibrated mean convection coefficient. This is done to ensure validity of the recalibration.

Measurements are taken at the frequency of one minute, and averaged to five-minute intervals [32]. Data gathered from Methods A and B will be used to recalibrate the globe thermometer to improve the accuracy of the globe thermometer with respect to radiant flux measurements. Table 2 shows the measured variables and equipment used.

The instrument setup used for the radiant flux measurements is shown in Fig. 1. A net radiometer with three integrated pyranometer and pyrgeometer arms (Kipp and Zonen, CNR 4), each measuring both incoming and outgoing short wave and long wave fluxes, are mounted on a steel tripod stand to measure the three-dimensional radiation field. Short wave and long wave radiation fluxes from the four cardinal points (North, East, South and West), as well as those from the upper and lower hemisphere, are measured. The newly purchased net radiometer was factory calibrated. The pyranometers were calibrated side by side to a reference CMP 3 pyranometer according to ISO 9847:1992 annex A.3.1. The pyrgeometers were calibrated side by side to a reference CG(R) 3 pyrgeometer [34].

In a previous study conducted in Sweden [32], the globe thermometer used consisted of a hollow acrylic sphere coated in flat grey paint (RAL 7001), with a diameter of 38 mm and a thickness of 1 mm, with a Pt100 sensor at its centre [28,29,31]. The 38 mm flat grey globe thermometer was mounted on the micrometeorological station.

Table 1
Measurement period.

	Study Area 1 Green Technology Laboratory rooftop	Study Area 2 School of Design and Environment Block 1 rooftop
Measurement date	28th February 2011 to 18th March 2011 30th March 2011 to 12th April 2011	13th August 2011 to 13th September 2011
No. of days measured	33	32
Purpose of measurement	Recalibration of mean convection coefficient to fit study	Validation of t_{mrt} calculation using recalibrated mean convection coefficient
No. of days used for recalibration of mean convection coefficient	33	–
No. of days used for validation of mean convection coefficient	–	32