Building and Environment xxx (2014) 1–14

Contents lists available at ScienceDirect

Building and Environment

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

Outdoor thermal comfort within five different urban forms in the Netherlands

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ARTICLE INFO

Article history:
Received 18 December 2013
Received in revised form
6 March 2014
Accepted 9 March 2014

Keywords:
Outdoor thermal comfort
Urban forms
PET
ENVI-met
Netherlands

ABSTRACT

Outdoor thermal comfort in urban spaces is known as an important contributor to pedestrians' health. The urban microclimate is also important more generally through its influence on urban air quality and the energy use of buildings. These issues are likely to become more acute as increased urbanisation and climate change exacerbate the urban heat island effect. Careful urban planning, however, may be able to provide for cooler urban environments. Different urban forms provide different microclimates with different comfort situations for pedestrians. In this paper, singular East–West and North–South, linear East–West and North–South, and a courtyard form were analysed for the hottest day so far in the temperate climate of the Netherlands (19th June 2000 with the maximum 33 °C air temperature). ENVI-met was used for simulating outdoor air temperature, mean radiant temperature, wind speed and relative humidity whereas RayMan was used for converting these data into Physiological Equivalent Temperature (PET). The models with different compactness provided different thermal environments. The results demonstrate that duration of direct sun and mean radiant temperature, which are influenced by urban form, play the most important role in thermal comfort. This paper also shows that the courtyard provides the most comfortable microclimate in the Netherlands in June compared to the other studied urban forms. The results are validated through a field measurement and calibration.

1. Introduction

Thermal comfort is defined as '*that condition of mind which expresses satisfaction with the thermal environment*' [1]. Since the 1980s, studies of thermal comfort in the outdoor environment have grown in number because of increased attention for pedestrians in urban canyons, plazas and squares. This led to a great number of researches addressing microclimate design parameters based on pedestrians' thermal comfort [2–9]. Thermal comfort in the outdoor environment is mainly related to thermo-physiology, i.e. physiology and the heat balance of the human body [10]. This field of study connects urban and landscape designers to bio-meteorology (more focus on pedestrians) and climatology (more focus on climate). Both bio-meteorologists and climatologists had important roles in developing thermal comfort indices such as the physiological equivalent temperature (PET) [11] and the universal thermal climate index [12]. With regard to different urban forms these indices have been well studied for hot arid and humid climates, but to a lesser extent for cooler environments, probably because in these climates people spend most of their times indoors. But considering climate change and the rise of global temperature makes outdoor thermal comfort more urgent [13,14].

The Netherlands has a temperate climate. Winters are milder than other climates in similar latitudes (and usually very cloudy) and summers are cool due to cool ocean currents. This country is faced with the effects of rapid climate change such as global temperature rise. Among different efforts, an appropriate urban design can help to mitigate heat stress for pedestrians. In this paper, five basic microclimates formed by simple urban forms are subject to analyses from a normal pedestrian's thermal comfort perspective. These analyses were conducted in the context of a representative meteorological city in the Netherlands: De Bilt. The aim of the study is to show which of the urban forms can provide a more comfortable microclimate on the hottest day of a year. Understanding the thermal behaviour of these microclimates allows landscape and urban designers to have clear guidelines for planning and design at their proposal.

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http://dx.doi.org/10.1016/j.buildenv.2014.03.014
0360-1323/

Table 1
Ranges of the thermal indexes predicted mean vote (PMV) and physiological equivalent temperature (PET) for different grades of thermal perception by human beings and physiological stress on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo [11].

PMV	PET °C	Thermal Perception	Grade of physiological stress
		Very cold	Extreme cold stress
-3.5	4		
		Cold	Strong cold stress
-2.5	8		
		Cool	Moderate cold stress
-1.5	13		
		Slightly cool	Slight cold stress
-0.5	18		
		Comfortable	No thermal stress
0.5	23		
		Slightly warm	Slight heat stress
1.5	29		
		Warm	Moderate heat stress
2.5	35		
		Hot	Strong heat stress
3.5	41		
		Very hot	Extreme heat stress

1.1. Outdoor thermal comfort indices

Howard [15] was the first who suggested to consider the effect of urban form on microclimate. In 1914 Hill, Griffith [16] made a big thermometer that indicated the influence of mean radiant temperature, air temperature and air velocity. Furthermore, Dufton [17] defined the equivalent temperature (T_{eq}) in 1929. This equivalent temperature, however, was only in use for a short period because environmental variables were not accounted for in the algorithms [18,19]. In addition, ASHRAE proposed and used the effective temperature (ET) from 1919 till 1967 [20]. In 1971, Gagge introduced ET* which was more accurate than ET because it simultaneously covered radiation, convection and evaporation. Around the same time, Fanger [21] developed theories of human body heat exchange based on PMV (Predicted Mean Votes) or PPD (Predicted Percentage Dissatisfied). Later on, this theory became the basis for indoor thermal comfort standards such as ISO 7730-1984 and ASHRAE 55-1992. Tahbaz [22] and Cohen, Potchter [7] have divided thermal indices into cold and hot climates:

a) Hot climates: Heat Stress Index (HIS) [23], Wet Bulb Globe Temperature (WBGT) [24], Discomfort Index (DI) [25], Index of Thermal Stress (ITS) [26], New Effective Temperature (ET*) [27], Skin Wettedness [28], Heat Index (HI) [29] and Tropical Summer Index (TSI) [30].
b) Cold climates: Wind Chill Index (WCI) and Wind Chill Equivalent Temperature (WCET) [31].

As a next step, the need for indices applicable to all climates and seasons led to a number of universal indices such as the Standard Effective Temperature (SET) [32], Perceived Temperature (PT) [33], Outdoor Standard Effective Temperature (OUT_SET) [34], Physiological Equivalent Temperature (PET) [35,36] and Universal Thermal Climate Index (UTCI) [37–39].

PET, or the physiological equivalent temperature (expressed by °C), tries to simplify the outdoor climate as an index for a lay person. This index is based on the Munich energy balance model for individuals (MEMI) [35,36,40] which is a thermo-physiological heat balance model. Such a model takes into account all basic thermoregulatory processes, such as the constriction or dilation of peripheral blood vessels and the physiological sweat rate. In detail, such models are based on the following equation:

$$S = M \pm W \pm R \pm C \pm K - E - RES \quad (1)$$

where S is heat storage, M is metabolism, W is external work, R is heat exchange by radiation, C is heat exchange by convection, K is heat exchange by conduction, E is heat loss by evaporation, and RES is heat exchange by respiration (from latent heat and sensible heat).

Actually, PET provides the equivalent temperature of an isothermal reference environment with a 12 hPa water vapour pressure (50% at 20 °C) and air velocity of 0.1 m/s, at which the heat balance of a lay person is maintained with core and skin temperature equal to those under the conditions in question. PET uses PMV (Table 1) as assessment scale, making it similar to a comfort index [11,41]. Finally, Matzarakis and Amelung [42] showed that PET is an accurate index for the assessment of the effects of climate change on human health and well-being. Last but not least, PET has the most important variables for human thermal comfort such as airflow, air temperature, radiant temperature and humidity. Moreover, the outcomes give a clear indication on the comfort temperature because it is still in degrees and therefore logical also for people that are no experts in meteorology. In this paper, PET – which has been tested and verified for the climate of North and West Europe [11,36,42] – is elaborated and used for the calculations of thermal comfort.

1.2. Urban typology study

Studies of the effect of urban form on outdoor microclimate are more recent than studies of indoor climate. Olgyay [43] and Oke [2]

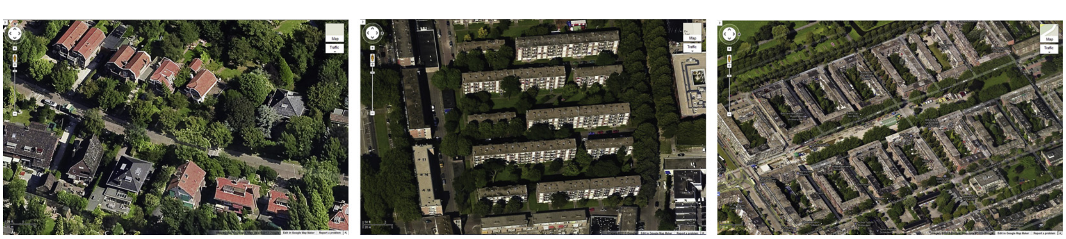

Fig. 1. Singular (left) linear (middle) and courtyard (right) urban forms in the Netherlands.

Please cite this article in press as: Taleghani M, et al., Outdoor thermal comfort within five different urban forms in the Netherlands, Building and Environment (2014), http://dx.doi.org/10.1016/j.buildenv.2014.03.014