Initial development of protocols for the study of outdoor thermal comfort

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356: Initial development of protocols for the study of outdoor thermal comfort

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Abstract

In this paper we review the micrometeorological and psychological instruments and methods used in ten thermal comfort studies reported in the literature during the last decade. The reviewed studies cover a wide range of climates and geographical contexts. The review reveals a great variety in instruments and methods used, especially when it comes to measuring or modelling the exchange of radiation between the human body and the surrounding urban environment, i.e. the mean radiant temperature; calculating the thermal comfort, i.e. thermal comfort indices used; and obtaining information on how people perceive the thermal conditions, i.e. the thermal comfort scales used in the questionnaires. It was concluded that the variety of instruments and methods used makes it difficult to compare results and that there is a need for standardization. Such protocols should contain guidelines regarding the choice of measurement sites, type and positioning of instruments, methods used to determine the mean radiant temperature, description of the urban environment around the measurement site, questionnaire design, suitable thermal comfort indices etc.

Keywords: thermal comfort, micrometeorological measurements, questionnaire surveys

1. Introduction

During the last decade a great number of studies on subjective outdoor thermal comfort in urban areas have been conducted and the number of studies tends to increase each year. These studies have been performed worldwide covering many different climates and cultures. Thus, a significant database exists. An interesting question is whether it would be possible to compare results and to calibrate thermal comfort indices in different climates and cultures in order to reveal differences in thermal comfort and thermal perception across different climates and cultures.

Such comparisons have been made earlier, e.g. within the European Union project RUROS, where researchers used similar methodologies to compare how the thermal comfort conditions and subjective thermal perception varied across Europe during different seasons of the year. However, this study did not present thermal comfort ranges of any commonly used thermal indices. [1]

A comparison between studies and determination of thermal comfort limits for different thermal comfort indices would require that the same instruments and methods are used when carrying out the different field campaigns, both as regards micrometeorological and psychological instruments and methods.

Today there is no international standard which covers thermal comfort field campaigns outdoors. Both ISO 7726 [2] and VDI 3787 [3] contain specifications for micrometeorological instruments and measurement techniques, but they do not deal with psychological instruments and methods, such as questionnaires and observation protocols. ISO 7730 [4] gives specification of the conditions for thermal comfort, but is limited to moderate thermal environments, i.e. mainly indoor environments.

The aim of this study was to review micrometeorological and psychological instruments and methods used in thermal comfort studies during the last decade. This is a first step towards standardisation of instruments and methods used for outdoor thermal comfort analyses

2. Methododology

2.1 Choice of studies

This paper is based on a literature review of ten studies on outdoor thermal comfort published during the latest decade, see Table 1. The review consists of the authors' own studies complemented with some other studies in order to cover more geographical regions and climate types. The studies were carried out in eight countries in the following climates: maritime temperate, humid subtropical, dry desert and dry steppe. When choosing the studies the requirement was that they should contain both micrometeorological measurements – to calculate the thermal comfort – and questionnaire surveys – to assess people's subjective thermal perception.

Table 1: Year of publication, geographical location and climate (according to Köppen's climate classification) of the ten compared studies.

Year	City	Climate	Ref.
2001	Cambridge, UK	Maritime temperate	[5]
2003	Sydney, Australia	Humid subtropical	[6]
2004	Gothenburg, Swe	Maritime temperate	[7]
2007	Matsudo, Japan	Humid subtropical	[8]
2009	Taichung, Taiwan	Humid subtropical	[9]
2011	Curitiba, Brazil	Maritime temperate	[10]
2011	Central Taiwan	Humid subtropical	[11]
2011	Cairo, Egypt	Dry desert	[12]
2012	Glasgow, UK	Maritime temperate	[13]
2012	Damascus, Syria	Dry steppe	[14]

Although this study dealt with only a limited number of all thermal comfort studies published, the comparison covers several different climates and cultures and gives a good picture of the instruments and methods that has been used over the last decade.

2.2 Comparison of methods used

The comparison covered general aspects such as in which seasons of the year and during which time of day that the field campaigns took place. Measurement techniques and questionnaire design were studied in detail.

The measurement techniques used in the reviewed studies were compared in terms of: parameters measured, measurement height, type and accuracy of instruments and choice of measurement sites. Moreover, the ways to determine the mean radiant temperature (MRT), which is a key parameter in outdoor thermal comfort, as well as the choice of thermal comfort indices, were studied.

The comparison of methods used to determine the subjective thermal perception included the number of subjects interviewed, the thermal perception scale used, whether the subjects were asked about their thermal preference as well as demographical information about the subjects. In addition questions regarding thermal history and acclimatization were compared between the studies.

Finally it was studied whether thermal comfort zones (upper and lower limits), the neutral temperature and the preferred temperature of thermal indices had been calculated based on the subjective thermal perception of the interviewees.

3. Results and discussion

3.1 Site selection and description

The chosen sites were normally well described – and often illustrated by photographs. However, the urban setting around the sites was often not described in detail.

3.2 Micrometeorological instruments and methods

Instrumentation

In most studies the types of instrument and their accuracy was stated. However, the instrumental setup proved to vary a great deal between the studies, especially as regards measurements of wind, radiation and globe temperature. The measurement probes were normally put at a standard 1.1 m height, but wind was often measured at higher heights, typically 2 m, and the wind speed at 1.1 m was estimated using the wind profile power law.

Wind measurements were performed using a large variety of anemometers such as three-dimensional sonic [8], two-dimensional sonic [14], cup [6,7,10,12,13] and heated-sphere [6]. Since wind speed is a critical parameter of assessing the thermal comfort accurate measurements are required. A cup anemometer has a threshold value which means that wind speeds below this level will not be registered and this instrument might thus be inappropriate at low wind speeds. Anemometers that only measure horizontal wind speeds – such as the cup anemometer and a two-dimensional ultrasonic anemometer – may underestimate the actual wind speed since urban winds often vary greatly in direction.

Fig 1. Instrument setup for measuring short- and long wave radiation fluxes from six directions (downward, upward, north, east, south, west) [16]

Determination of MRT

MRT is one of the most important parameters in assessing the thermal comfort, especially in summer [15]. It considers both short-wave and long-wave radiation and represents the weighted average temperature of an imaginary enclosure that gives the same radiation as the complex urban environment [16]. The most accurate way to determine the MRT is by measuring the short- and longwave radiation from six directions using pyranometers and pyrgeometers, see Fig. 1. This equipment is however expensive and rarely available.

In this review it was found that the methods used to determine the MRT varied greatly between the studies, see Table 2. Most studies, used a globe thermometer (see Fig. 2) combined with measurements of air temperature and wind speed to determine MRT. Another common way to determine the MRT was by using the RayMan model based on measurements of incoming global radiation and geometrical modelling of the site. One of the studies [6] measured the MRT using incoming (downward) and outgoing (upward) shortwave (direct and diffuse) and long-wave radiation. None of the studies used three-dimensional measurements.

Table 2: Ways to measure/calculate MRT in the reviewed studies.

Measurements	No. of studies	Ref.
Globe temp., air temp., wind speed	6	[5,8,10, 12,13,14]
Incoming and outgoing shortwave (direct and diffuse) and longwave radiation	1	[6]
Incoming global shortwave radiation and modelling with RayMan	5	[7,8,9, 10,11]

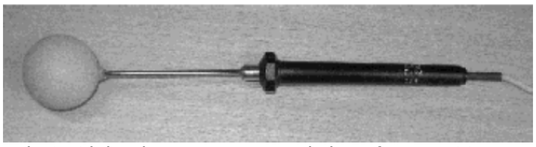

Fig 2. Globe thermometer consisting of a grey 38 mm acrylic ping pong ball around a Pt100 temperature probe [16]

To determine MRT through measurements with a globe thermometer, both the globe temperature (i.e. the equilibrium temperature of the thermometer inside the globe) and the convective heat losses of the globe need to be known. The latter depend on the wind speed. However, if the globe thermometer is large and heavy it may take up to 20 min to reach equilibrium [6]. Thus globe thermometers having a large time constant are not well suited to measure the MRT outdoors where radiative fluxes and wind speed are changing rapidly [6]. The formula to calculate MRT depends on the type of globe, see [14,16]. Ideally the MRT formula should be determined through calibration with three-dimensional measurements of short- and longwave radiation fluxes according to Fig. 1[16]. Moreover, the MRT calculated from a globe thermometer is sensitive to variations in wind speed. E.g. a sudden increase in wind speed will mean that the globe cools down, but as this will take some time to happen, MRT will be overestimated. Similarly a sudden decrease in wind speed will lead to an underestimated MRT. To reduce the sensitivity to wind speed variations, 5 to 10 minute averages should be used in the calculations of MRT [16].

As can be seen in Table 3 the types of globe thermometer used in the reviewed studies varied greatly.

Table 3: Types of globe thermometer used.

Material	Diam. (mm)	Colour	No. of studies	Ref.
Acrylic	40	Grey	2	[8,14]
Copper	50	Grey	1	[10]
n/a	110	Grey	1	[13]
n/a	n/a	n/a	2	[5,11]

Thermal indices used

The different studies have calculated different thermal comfort indices, see Table 4. Some studies have used several indices. The most commonly used index was the Physiological Equivalent Temperature (PET).

Table 4: Thermal indices used in the studies.

Index	No. of studies	Ref.
PET – Physiological Equivalent Temperature	6	[6,8,9,12, 13,14]
SET* – Standard Effective Temperature	3	[6,11,14]
PMV – Predicted Mean Vote	2	[5,7]
PT – Perceived Temperature (derived from PMV)	1	[6]
Others	3	[6,10,13]

3.3 Psychological instruments and methods

Questionnaires

The number of subjects varied greatly between about 300 and 1700. However, studies with many subjects normally concerned surveys conducted over long time periods (several seasons). The majority of the studies covered at least two seasons, see Table 5.

Table 5: Number of subjects interviewed in the different studies.

Year	City	Season	No. of sub-jects	Ref.
2001	Cambridge, UK	All year	1431	[5]
2003	Sydney, Australia	Sum./win.	1018	[6]
2004	Gothenburg, Swe	Sum./aut.	285	[7]
2007	Matsudo, Japan	Spring	1142	[8]
2009	Taichung, Taiwan	All year	n/a	[9]
2011	Curitiba, Brazil	½ year	1654	[10]
2011	Central Taiwan	All year	1644	[11]
2011	Cairo, Egypt	Sum./win.	300	[12]
2012	Glasgow, UK	Spr./sum.	567	[13]
2012	Damascus, Syria	Sum./win.	920	[14]

Table 6: The different thermal sensation scales used in the studies.

Value	5-point	7-point	9-point
-4	Very cold		Very cold
-3		Cold	Cold
-2	Cool	Cool	Cool
-1		Slightly cool	Slightly cool
0	Neutral	Neutral	Neutral
+1		Slightly warm	Slightly warm
+2	Warm	Warm	Warm
+3		Hot	Hot
+4	Very hot		Very hot

All studies included a question on thermal comfort/perception of the type “How do you perceive the weather right now?”. However, different thermal perception scales were used, see Table 6. The by far most commonly used scale was the ASHRAE 7-point [6,7,9,10,11,12,13]. Two studies used a 9-point [8,14] and one study a 5-point scale [5].

In half of the studies [6,9,10,11,14] the question about thermal perception was complemented by a question on thermal preference: “How would you like to be?”. In the case where a 3-point scale was used the response options were: “warmer”, “no change” or “cooler”.

In addition to questions related to thermal comfort, several other questions were asked, see Table 7. Basically all studies collected information about age, gender, clothing and activity, whereas questions regarding thermal history were reported in only six of the studies.

Table 7: Additional questions.

Question/observation	No. of studies	Ref.
Age and gender	10	[5,6,7,8,9,10, 11,12,13,14]
Clothing and activity level	9	[5,6,7,8,10,11 ,12,13,14]
Time spent outdoors	6	[6,7,8,10, 13,14]
Reason for being at the site	4	[7,8,9,14]
Frequency of visiting the site	2	[8,14]
Time of residency	2	[10,13]

3.4 Calibration of thermal comfort indices

In seven of the studies the comfort zone of one or more indices was defined [6,9,10,11,12,13,14]. In as many as eight studies the neutral index temperature was determined [5,6,9,10,11,12,13, 14] whereas in only three studies the preferred temperature was determined [6,9,11].

4. Conclusions and future work

This review concluded that there is a great variety of micrometeorological and psychological instruments and methods used in outdoor thermal comfort studies. There is thus an obvious need for standardization and to give guidance regarding how to perform field campaigns.

In particular, there is a need to:

- Standardize instruments and methods to determine the MRT and wind speed
- Standardize questionnaires, i.e. which thermal perception scale to use, which questions to ask, wording, etc.
- Standardize reporting (format and content)

Future work should aim at developing protocols which should include recommendations in terms of choice of measurement sites, description of the urban environment around the measurement site, minimum no. of subjects, type and minimum accuracy of instruments, positioning of instruments, questionnaire design, suitable thermal comfort indices, etc.

5. References

1. Nikolopoulou, M. and S. Lykoudis, (2006). Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment*, 41: p. 1455–1470.
2. ISO 7726, (1998). Ergonomics of the thermal environment – Instruments for measuring physical quantities. International Organization for Standardization, Geneva.
3. ISO 7730, (2005). Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Organization for Standardization, Geneva.
4. VDI, (2008). VDI 3787 Environmental meteorology – Methods for the human biometeorological evaluation of climate and air quality for urban and regional planning at regional level – Part I: Climate. In VDI-Handbuch Reinhaltung der Luft, Bd. 1 b.
5. Nikolopoulou, M., N. Baker and K. Steemers, (2001). Thermal comfort in outdoor urban spaces: understanding the human parameter. *Solar Energy,* 70: p. 227–235.
6. Spagnolo, J. and R. de Dear, (2003). A field study of the thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Building and Environment,* 38: p. 721–738.
7. Thorsson, S., M. Lindqvist and S. Lindqvist, (2004). Thermal bioclimatic conditions and patterns of behavior in an urban park in Göteborg, Sweden. *Int. Journal of Biometeorology,* 48: p. 149–156.
8. Thorsson, S., T. Honjo, F. Lindberg, I. Eliasson and E. M. Lim, (2007). Thermal comfort and outdoor activity in Japanese urban public places. *Environment and Behavior*, 39: p. 660-684.
9. Lin, T.-P., (2009). Thermal perception, adaptation and attendance in a public square in hot and humid regions, *Building and Environment*, 44: p. 2017-2026.
10. Krüger, E. L. and F. A. Rossi, (2011). Effect of personal and microclimatic variables on observed thermal sensation from a field study in southern Brazil. *Building and Environment*, 46: p. 690-697.
11. Lin, T.-P., R. de Dear and R. L. Hwang, (2011). Effect of thermal adaptation on seasonal outdoor thermal comfort. *Int. Journal of Climatology,* 31: p. 302–312.
12. Mahmoud, A. H. A., (2011). Analysis of the microclimatic and human comfort conditions in an urban park in hot and arid regions. *Building and Environment,* 46: p. 2641–2656.
13. Krüger, E., P. Drach, R. Emmanuel and O. Corbella, (2012). Urban heat island and differences in outdoor comfort levels in Glasgow, UK. *Theoretical and Applied Climatology*, 109 (online). DOI 10.1007/s00704-012-0724-9.
14. Yahia, M. W. and E. Johansson, (2012). Evaluating the behaviour of different thermal indices by investigating various outdoor urban environments in the hot dry city of Damascus, Syria. *Int. Journal of Biometeorology* (In press). DOI 10.1007/s00484-012-0589-8
15. Mayer, H. and P. Höppe, (1987). Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*, 38: p. 43-49.
16. Thorsson, S., F. Lindberg, I. Eliasson and B. Holmer, (2007). Different methods for estimating the mean radiant temperature in an outdoor urban setting. *Int. Journal of Climatology*, 27: p. 1983-1893.