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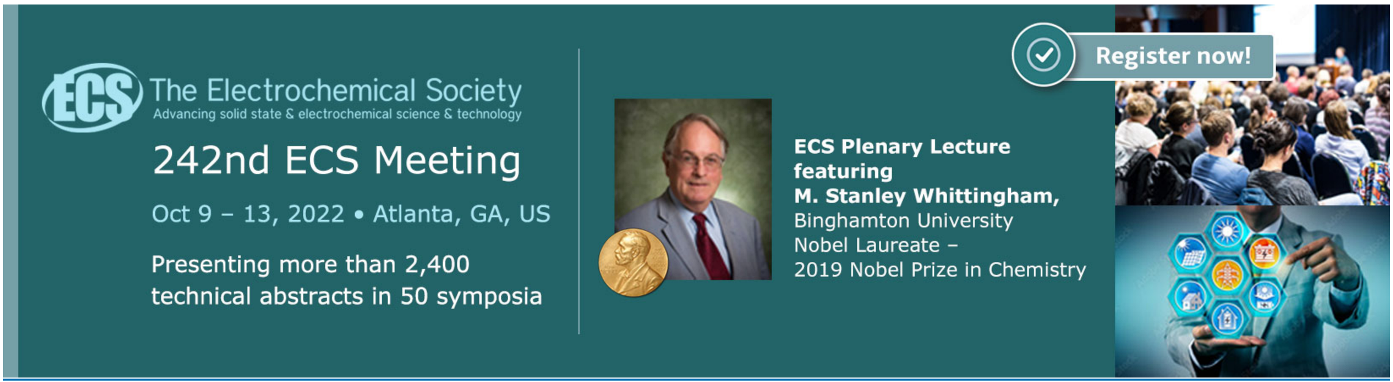

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Uncertainty Analysis of the Mean Radiant Temperature Measurement based on Globe Temperature Probes

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Abstract. Nowadays, due to the importance that aspects related to energy efficiency and indoor environmental quality have assumed, the need to carry out audits in which the thermal comfort indices are assessed has grown substantially. A particularly relevant issue is the quality of the experimental results, which is directly connected to the uncertainty of the indices values. The evaluation can be based on the PMV-PPD indices or on the Adaptive Model method, and in both an inescapable environmental variable is the mean radiant temperature. It can be obtained from different methods, being the most used the one based upon the simultaneous measurement of the globe temperature, the air temperature and the air speed. In the work reported in this paper, the impact of the aforementioned environmental variables and their uncertainties on the combined expanded uncertainty of mean radiant temperature has been studied, for two diameters of the globe temperature probe and for two metrological quality conditions of the used probes. The calculations were performed using the Monte Carlo method.

1. Introduction

The Mean Radiant Temperature is a fundamental variable for the evaluation of the quality of indoor thermal environments. It is defined as the uniform temperature of an imaginary enclosure where the occupant would exchange the same amount of heat by radiation as in the actual room. Mathematically it is the weighted average of the temperatures of the surfaces surrounding the measuring point, being the weighting coefficients the so-called view factors. Several methods are used to measure it [1], [2], being the most used the one based on the simultaneous measurement of the globe temperature, the air temperature and the air speed. The globe temperature probe was introduced by Vernon in 1930 as a method of assessing the combined effects of radiation and convection on human thermal sensation.

The measurement accuracy of the thermal environment related parameters has been addressed by several authors [3], [4], [5], but a more detailed analysis of the influence of the factors affecting the uncertainty associated to the calculation of Mean Radiant Temperature is justified. Like other environmental physical variables used to characterize the indoor climate quality, e.g. air speed, it poses some difficulties to get it with low uncertainty, since it is not measured by a unique probe, but is usually obtained by a calculation method with various inputs, thus, implying a rise in the number of error sources and the consequent propagation of errors.

2. Method

In the calculation of the Mean Radiant Temperature (T_r), based upon a Globe Temperature probe (T_g), an equation derived from the thermal balance of the globe's body, assuming symmetrical contributions from convection and radiation, is used,

$$\varepsilon\sigma(\bar{T}_r^4 - T_g^4) + h_{cg}(T_a - T_g) = 0 \qquad (1)$$

which, isolating the Mean Radiant Temperature in the first member, gives:

$$\bar{T}_r = \sqrt[4]{T_g^4 + \frac{h_{cg} \times (T_a - T_g)}{\varepsilon\sigma}} \qquad (2)$$

In case the result is wanted in ºC, instead of an absolute temperature, it becomes

$$\bar{t}_r = \sqrt[4]{\left(t_g + 273\right)^4 + \frac{h_{cg} \times (T_a - T_g)}{\varepsilon\sigma}} - 273 \qquad (3)$$

where:
σ–Stephan-Boltzman Constant (W · m^{-2} ·K^{-4})
ε - Emissivity (dimensionless)
h_{cg}–Convection heat transfer coefficient (W.m^{-2} K)
T_a – Absolute temperature of air (K)

The value of h_{cg} is, in each case, the highest of the two values for the natural and the forced convection coefficients, defined, respectively, as:

$$h_{cg_{nat}} = 1.4 \sqrt[4]{\frac{\Delta t}{d}} \qquad (4) \qquad\qquad h_{cg_{forc}} = 6.3 \times \frac{v_a^{0.6}}{d^{0.4}} \qquad (5)$$

The uncertainty analysis has been carried out with the application of the Monte Carlo simulation method [6]. An application tool has been developed in the programming language LabView. The input variables were oscillated assuming a normal probability distribution for their uncertainty errors. The two conditions defined in ISO 7726, for the metrological quality of measuring probes (Required and Desirable), were considered (see Table 1).

Table 1. Uncertainties of Indoor Environmental Variables (ISO 7726:1998)

	Required	**Desirable**
Air/Globe Temperature (ºC)	± 0.5	± 0.2
Mean Radiant Temp (ºC)	± 2	± 0.2
Air Speed (m/s)	A = 0.05	A = 0.02
	B = 0.05	B = 0.07

The used number of repetitions in the Monte Carlo simulation method has been fixed in 25 000, after a preliminary study on the stability of the results over repeated runs of the software has been performed.

3. Results

The presented results concern the values of the expanded uncertainty of Mean Radiant Temperature, obtained multiplying by a coverage factor equal to 2 (95% probability), the standard deviation of the 25 000 values series obtained from the Monte Carlo simulations. In Figure 1, the expanded uncertainty values of T_r, are represented as a function of ΔT (t_a-t_{globe}) and the the flow speed (v), for a 150 mm globe diameter and for two metrological quality conditions of the measuring probes [a) for "Required" and b) for "Desirable"].

The uncertainty values for the least demanding situation concerning the quality of probes, i.e. "Required conditions", are typically doubling those obtained for the "Desirable conditions". From the analysis of the figures, it can also be concluded that there is a strong change in the evolution of the uncertainty errors for flow speeds higher than 0.1 m/s, when the change from natural to forced convection occurs. It should be stated that, in a high percentage of the conditions occurring in the analysis of indoor thermal comfort, the temperature difference ΔT will remain between -5 ºC and 5ºC, even if the results are depicted for a wider range.

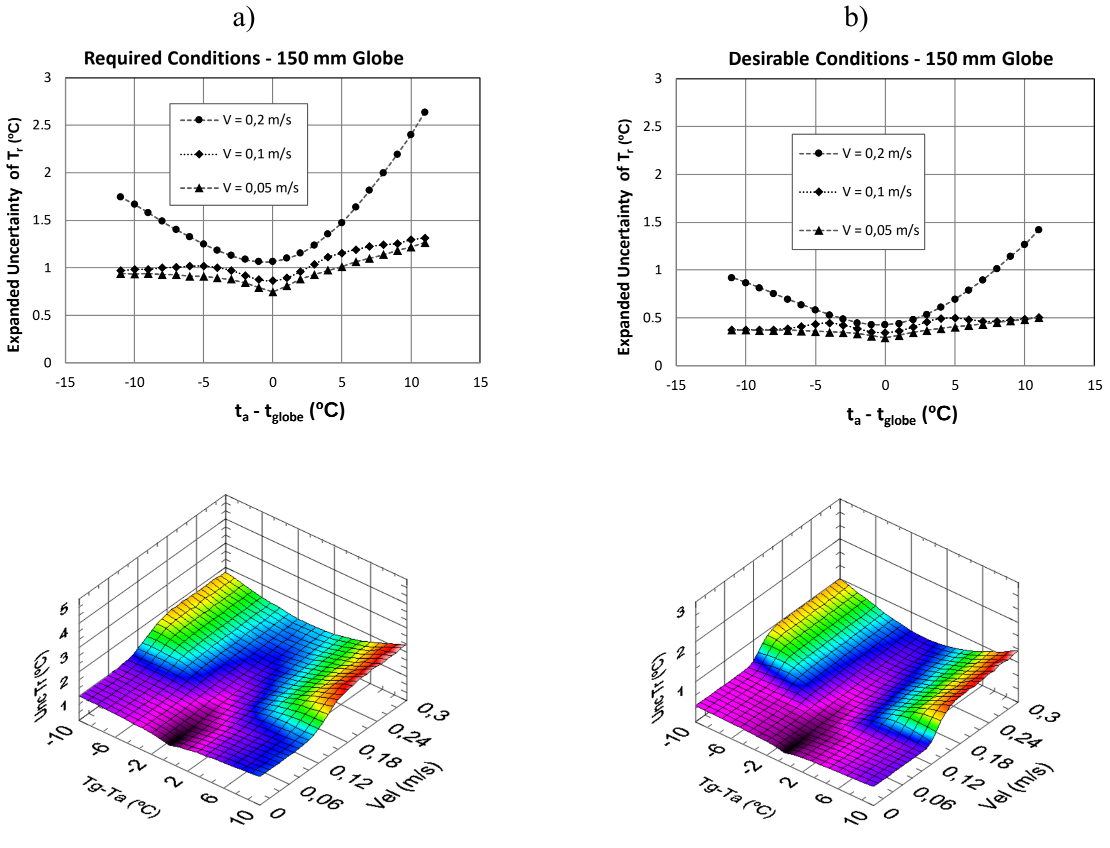

Figure 1. Expanded uncertainty of Mean Radiant Temperature, for the Required (a) and Desirable (b) metrological conditions of probes defined in ISO 7726, Globe diameter equal to 150 mm.

In Figure 2, a comparison between the behaviour of 150 mm and 40 mm diameter globes is presented. Due to the high response time of the original Globe Temperature probe (d=150 mm) when subjected to a step input, that is about 25 minutes, smaller globes are used. The response time, in the case of 40 mm diameter globe is reduced to about 10 min. Analysing Figure 2, it can be seen that there is a worst behaviour, with respect to the uncertainty, for the smaller probe. The base value of the uncertainty, for v = 0 m/s, is slightly higher, the transition in the behaviour appears sooner for air speeds higher than 0.06 m/s, and the maximum values are almost doubling those of the 150 diameter globe.

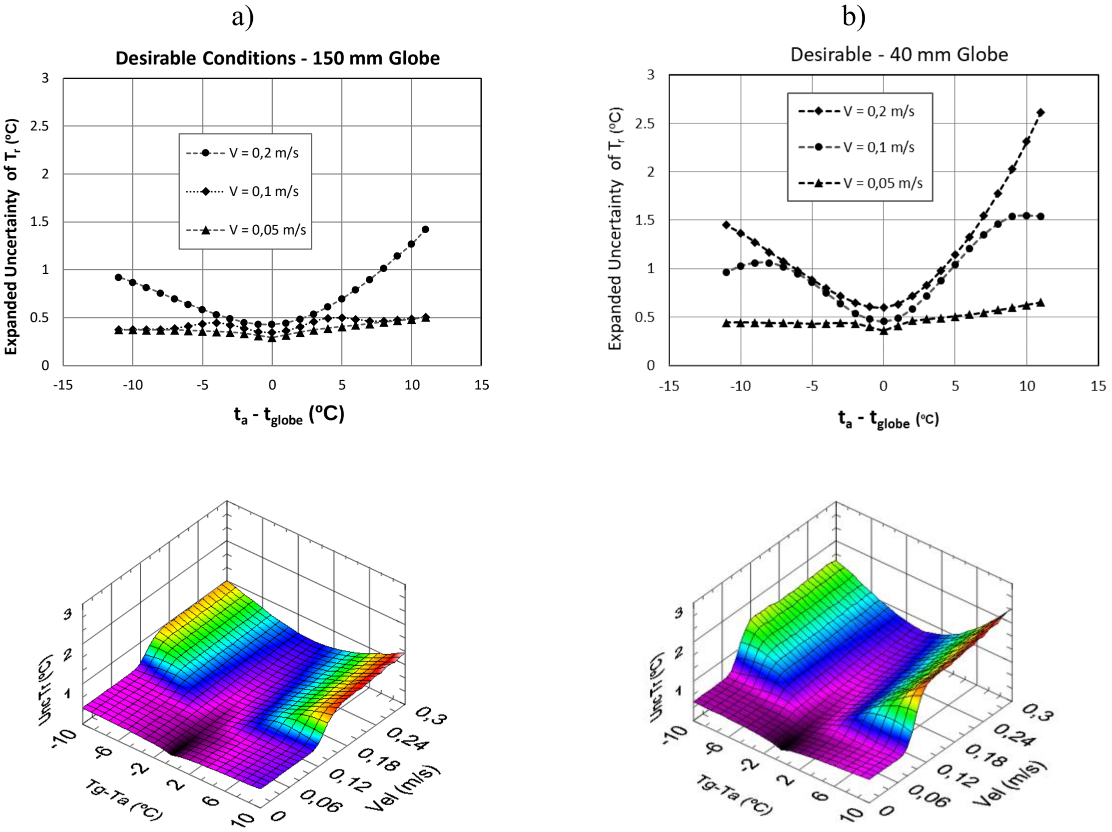

Figure 2. Expanded uncertainty of Mean Radiant Temperature, for the Desirable metrological conditions of probes defined in ISO 7726, for two diameters of the Globe Temperature Probe.

4. Conclusions

An analysis of the uncertainty of Mean Radiant Temperature has been performed, using a Monte Carlo simulation, for the measuring procedure based on the use of a Globe Temperature Probe. Interesting findings about the impact of various parameters arise as an outcome of the presented work, namely the influence of the globe diameter and the quantification of the effect of the metrological quality of the probes used to perform the measurements. High air speeds, high differences between Ta and Tg and small globes increase the uncertainty of measurements The main recommendations, to improve the accuracy of mean radiant temperature measurements based on globe temperature sensor, are to use the big 150 mm diameter globe and Desirable quality measuring probes.

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