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On the measurement of the mean radiant temperature and its influence on the indoor thermal environment assessment

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ABSTRACT

The mean radiant temperature is one of the six main variables responsible for the thermal sensation of the man exposed in a particular thermal environment (indoor and outdoor). Its measurement is not direct and is usually carried out by means of different methodologies and instruments whose general details and accuracy requirements are reported in the ISO Standard 7726. This paper deals with a critical review on the typical measurement methodologies combined with a comparative analysis of the metrological performances exhibited by the more common practice instruments on the market. To this purpose a special room-test has been designed aiming to reproduce the typical microclimatic conditions can be encountered in workplaces both in summer and in winter conditions. The effect of the measurement methodology and used instruments on the thermal comfort (global and local) and the thermal stress assessment has been finally discussed. Obtained results show that the use of different instruments consistent with ISO Standard 7726 requirements results in values of the mean radiant temperature compatible with each other, but the consequences on thermal environment assessment appear often ambiguous. Obtained results have focused the need for starting an in-depth discussion on the measurements' protocols and the instruments leading to a possible reduction of the required accuracy levels reported in the ISO Standard 7726.

1. Introduction

According to the rational approach [1,2], the evaluation of the thermal environments requires the knowledge of six quantities: two subjective (the clothing thermal insulation and the metabolic rate) and four physical (the air temperature, the mean radiant temperature, the air velocity and the air humidity). These parameters have to be measured or estimated in order to calculate, depending on the situation, the suitable comfort [1] or stress index [3–5] and lead to the thermal environment assessment.

Concerning moderate environments where the main goal is to keep comfort conditions for the occupants, the mean radiant temperature t_r (defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform enclosure) is a very significant factor especially in buildings whose envelopes were exposed to a strong solar radiation [6]. As a matter of fact, warm surfaces may cause a person to feel warmer than the surrounding air temperature would indicate and likewise cold walls or windows may bring to feel cold even though the surrounding air may be at a comfortable level. In moderate environments, apart from a trivial effect on the energetic costs of the building [7] and the productivity [8] this phenomenon can also lead to the asymmetry of the radiative heat flow around the person with the consequent onset of local thermal discomfort [9–12]. Under typical working conditions (e.g. industry, constructions), apart from working activities carried out outdoors [13] in the presence of high solar loads, high and low radiative load sources have to be treated with high care also in several workplaces as baking, car manufacturing, glass factories, foundries, mines, freezer rooms and so on to avoid the onset of heat and cold disorders [14].

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2. Mean radiant temperature measurement and peculiarities of the instruments

The methodologies devoted to the assessment of the mean radiant temperature under indoor conditions – standardized by the ISO Standard 7726 [15] – are not easy nor friendly matters and they are slightly different, to those commonly used outdoors [16,17] due to the contribution of the solar radiation. The Standard takes into account three methods (based on the black globe temperature, the two sphere radiometer and the constant-air-temperature sensors) and two calculation procedures (based on the angle factors between the person and the surrounding surfaces and on the plane radiant temperatures). Moreover it suggests how convert into a t_r value the measurement of the absolute radiant heat flow defined by the Stefan–Boltzmann's equation and the effective radiant heat flow [18] between the surfaces of the environment and the person (by assuming skin temperature and clothing emissivity values $t_{sk} = 32$ °C and $\varepsilon = 0.95$, respectively).

The ISO Standard 7726 suggests also different characteristics of the instruments to be used for the measurement of the mean radiant temperature by classifying them into class C (comfort) and class S (stress) depending on the kind of the thermal environment (moderate or extreme cold/hot). In Table 1 the main characteristics of instruments devoted to the measurement of the mean radiant temperature in moderate and in severe environments are reported [15].

Table 1
Main characteristics of the instruments devoted to the measurement and the calculation of the mean radiant temperature in moderate environments (class C) and in severe environments (class S) according to ISO 7726 standard [15].

	Quantity	Range of measurement	Accuracy
Class C (Comfort)			
Direct methods	t_r	10–40 °C	Required: ±2 °C Desirable: ±0.2 °C *Values hard to guaranteed with instruments available on the market. If not guaranteed it is necessary to indicate the real accuracy.*
Indirect methods	t_{pr}	0–50 °C	Required: ±0.5 °C Desirable: ±0.2 °C *These values shall be guaranteed for* $/t_{pr} - t_a/ < 10$ °C
	t_s	0–50 °C	Required: ±1 °C Desirable: ±0.5 °C
Class S (Stress)			
Direct methods	t_r	−40 to + 150 °C	Required: −40 to 0 °C: $\pm(5 + 0.02\ \lvert t_a \rvert)$ °C >0–50 °C: ±5 °C >50–150 °C: $\pm[5 + 0.08\ (t_r - 50)]$ °C Desirable: −40 to −0 °C: $\pm(0.5 + 0.01\ \lvert t_r \rvert)$ °C >0–50 °C: ±5 °C >50–150 °C: $\pm[0.5 + 0.04\ (t_r - 50)]$ °C
Indirect methods	t_{pr}	0–200 °C	Required: −60 to 0 °C: $\pm(1 + 0.1\ \lvert t_{pr} \rvert)$ °C >0–50 °C: ±1 °C >50–200 °C: $\pm[1 + 0.1\ (t_{pr} - 50)]$ °C Desirable: Required accuracy/2 *These values shall be guaranteed at least for a deviation* $\lvert t_{pr} - t_a \rvert < 20$ °C
	t_s	−40 to + 120 °C	Required: < −10 °C: $\pm[1 + 0.05(-t_s - 10)]$ °C −10 to 50 °C: ±1 °C >50 °C: $\pm[1 + 0.05\ (t_s - 50)]$ °C Desirable: Required accuracy/2

Note: the response time (90%) for all the instruments has to be the shortest possible and should be specified as characteristic of the measuring instrument.

2.1. Instruments available on the market

Several devices for measuring the mean radiant temperature are actually available on the market [19–22]. The most popular instrument is undoubtedly the globe thermometer, due to the low cost and a high traceability. Unfortunately it is affected by high response times (with the consequent impossibility to carry out running measurements) and, because of its spherical shape, it overestimates the radiative contribution related to horizontal surfaces (ceiling and floor). Moreover the globe does not allow the assessment of the radiant temperature asymmetry that is one of the four responsible for local thermal discomfort in moderate environments [9,23,24].

The contact thermometers and the radiation thermometers are also widely used. Contact thermometers are cheap but, unless used with great care and attention, may provide unreliable values of the measured variable mainly due to the contact resistances. Radiation thermometers require the knowledge of the emissivity value of the surface to be measured. Unlike the globe thermometer both these instruments allow the evaluation of the asymmetry of the radiant temperature.

Finally, the net radiometers for the direct measurement of the mean radiant temperature are quite expensive and require the use of more sensors or measurements in the three directions for the calculation of the values of plane radiant temperature [22].

In Table 2 a thorough comparison between the different methods for the evaluation of the mean radiant temperature is summarized.

Because of the high costs, the time required for the measurements and their complexity it is almost trivial that the choice of the instrument for the measurement of the mean radiant temperature cannot be made on the only base of the compliance with ISO Standard 7726 requirements. In fact: (a) the methods briefly summarized in Table 2 require to pay attention and skilled users; (b) a correct choice of the instruments depends on the kind of thermal environment (e.g. unlike hot and cold extreme environments, in moderate ones the assessment of the local discomfort requires the measurement of the plane radiant temperatures [23,24]) or on the need for a continuous measurement of the thermal flows in the environment.

Beyond these topics, another crucial facet makes the measurement of the mean radiant temperature in environment a very delicate matter. Above all, the mean radiant temperature can be measured only by indirect procedures, therefore the requirements of the accuracy cannot be referred to the single instruments (as in ISO Standard 7726) rather the measurement method adopted. As a consequence the different values of the measurand can be related both to the instrument and the method implemented [25].

3. Aim of the paper

Referring to moderate thermal environments it has been stressed by several researchers how their classification based on PMV values seems to be so strongly prescriptive to make almost

Table 2
Comparison among the different evaluation methods of the mean radiant temperature.

Method and equations	Advantages	Disadvantages
Measurements methods		
Globe $T_r = \sqrt[4]{T^4{}_g + \frac{h_{cg}}{\varepsilon_g \sigma}(T_g - T_a)}$	- Method friendly to be used mainly due to: - compact equipment; - easy calculation; - direct assessment of the radiative thermal load on the person. - Low cost - Standard diameter	- Relevant measurement uncertainties due to: - convective and radiative heat transfer coefficients usually approximated; - subject shape is not a sphere with the consequent overestimation of the radiative thermal flows related to the horizontal surfaces of the environment; - the black paint of the globe shows an emissivity value different to that exhibited by the clothing (especially in case of direct exposition to the solar radiation). - *Discrete measurement* (not suitable for heterogeneous environments) - *High response time* (20–30 min about).
Two sphere radiometer (spherical or ellipsoidal) $T_r = \sqrt[4]{T_s^4 + P_p - P_b/\sigma\cdot(\varepsilon_b - \varepsilon_p)}$	- Compensation of the convective thermal load - direct assessment of the radiative thermal load on the person.	- Measurement uncertainties due to: - subject shape is not a sphere; - different spatial position of the spheres; - black paint emissivity; - emissivity of the reflective sphere (it increases during the time); - complexity of the thermostating loop of the spheres. - Discrete measurement - Not enough widespread - High response time
Constant-air-temperature sensor (spherical or ellipsoidal): $T_r = \sqrt[4]{T_s^4 - P_s/\sigma\cdot\varepsilon_s}$	- Compensation of the convective thermal load - direct assessment of the radiative thermal load on the person.	- Measurement uncertainties due to: - subject shape is not a sphere; - emissivity of the sensor - complexity of the thermostating loop of the spheres (*especially if* $t_r > t_a$) - Discrete measurement - Not enough widespread
Method based on the measurement of the effective radiative flow $T_r^4 = T_b^4(1 + 2.15 \times 10^{-3}\cdot E_{eff})$	• Highest accuracy as the measurement is not related to the emissivity • Versatility due to the possibility of studying transient phenomena.	• Complexity of the method because the radiant flow measurement has to be carried out over the three directions • Not enough widespread • Discrete measurement
Calculation methods		
Method based on the temperature of the surrounding surfaces and angle factors: $T_r^4 = T_1^4\cdot F_{p-1} + T_2^4\cdot F_{p-2} + \ldots + T_N^4\cdot F_{p-N}$	- Good accuracy due to: - contact temperature measurement; - calculation of the single surface terms contributing to t_r. - Versatility due to the possibility to: - study transient phenomena; - assess the radiant field of the environment; - assess the asymmetry conditions.	- Complexity of the method due to: - contact measurement hard to be carried out; - need for the measurement of all the surface temperatures of the environment; - required equipment; - need for radiometers for the measurement of the solar load in the presence of transparent surfaces; - hard calculation of the angle factors in case of non-standard geometries.
Method based on the angle factors and remote thermometers/thermographs $T_r^4 = T_1^4\cdot F_{p-1} + T_2^4\cdot F_{p-2} + \ldots + T_N^4\cdot F_{p-N}$	- Highest accuracy due to: - possibility to carry out several measurement of the surface temperature (thermograms also); - calculation of the single surface terms contributing to tr. - Versatility due to the possibility to: - study transient phenomena; - assess the radiant field into the environment; - assess the asymmetry conditions.	- Complexity of the method due to: - assessment of the emissivity of the surfaces; - equipment required for the measurement of the temperature of the opaque surfaces and need for radiometers for the assessment of the solar load in the presence of transparent surfaces; - hard calculation of the angle factors in case of non-standard geometries.

(*continued on next page*)

Table 2 (*continued*)

Method and equations	Advantages	Disadvantages
Methods based on plane radiant temperature measurements		
Method based on the net radiometerorientation not fixed $T_r^4 = T_1^4 \cdot F_{p-1} + T_2^4 \cdot F_{p-2} + \ldots + T_N^4 \cdot F_{p-N}$ with $T_{pr-i} = \sqrt[4]{0.95 \cdot T_n^4 + P_i/\sigma}$	- Compensation of the convective thermal load - Versatility of the method due to the possibility of measuring asymmetries.	- Uncertainties related to: - the different spatial position of the disks; - the emissivity of the black paint; - the emissivity of the reflective disk increases over the time; - complexity of the thermostating loop of the disks - Discrete measurement - Not enough widespread - High response time
Method based on the constant-air-temperature disk orientation not fixed STANDING $t_r = 0.06(t_{pr,up} + t_{pr,down}) + 0.220(t_{pr,front} + t_{pr,rear} + t_{pr,left} + t_{pr,right})$ SITTING $t_r = 0.13(t_{pr,up} + t_{pr,down}) + 0.185(t_{pr,front} + t_{pr,rear} + t_{pr,left} + t_{pr,right})$ with $T_{pr} = \sqrt[4]{T_s^4 - (P_s/\sigma \cdot \varepsilon_s)}$	- *Compensation of the convective thermal load* - *Versatility of the method due to the possibility of measuring the asymmetries.*	- Uncertainties related to: - the emissivity of the black paint; - complexity of the thermostating loop of the disks - Discrete measurement - Not enough widespread
Method based on a heated sensor consisting of with an absorbing disk and a reflective disk orientation not fixed STANDING $t_r = 0.06(t_{pr,up} + t_{pr,down}) + 0.220(t_{pr,front} + t_{pr,rear} + t_{pr,left} + t_{pr,right})$ SITTING $t_r = 0.13(t_{pr,up} + t_{pr,down}) + 0.185(t_{pr,front} + t_{pr,rear} + t_{pr,left} + t_{pr,right})$ with $T^4{}_{pr} = T_s^4 + (P_p - P_b/\sigma(\varepsilon_p - \varepsilon_b))$	- *Compensation of the convective thermal load* - *Versatility of the method due to the possibility of measuring the asymmetries.*	*Uncertainties related to:* - the emissivity of the black paint; - complexity of the thermostating loop of the disks - *Discrete measurement* -*Not enough widespread* - *High response time*

impossible its practical use [27–30]. In particular, in naturally conditioned spaces according to De Dear's group findings based over thousand and thousand questionnaires [27] it seems that thermal environmental quality A class [27] confers no relative satisfaction benefit to individuals or to realistic building occupancies. Moreover, the numerical results of the sensitivity analysis of the PMV index with respect to the six quantities by which it is affected [28,29] revealed that although the mean radiant temperature measurement is carried out within the accuracy requirements expected by the ISO 7726 Standard, PMV value can vary till to make quite random the classification of the environment. On the contrary, milder sensitivities of the PMV with respect to the air velocity and the air temperature were revealed (or negligible in the case of the humidity for environments under class A and B conditions [31]). These results were also confirmed by a further analysis of uncertainties reported in another investigation by our team [30]. In particular, it has been proved that a class A unambiguous attribution is difficult and often impossible unless the use of instruments with very good accuracy (for example, with instruments exhibiting the best uncertainty) and in homogeneous and steady-state environments. Moreover, the use of different instruments consistent with ISO 7726 requirements results in values compatible with each other, but the class attribution remains often ambiguous. A similar behavior was also stressed under hot environments conditions (class S). In fact, the PHS index is strongly affected by mean radiant temperature value [32] and this sensitivity is further amplified since the accuracy requirements of instruments under class S are less prescriptive than those under class C [15] as shown in Table 1.

Finally, in the literature of the field the only studies devoted to the mean radiant temperature deal either with the characterization of the measurement method for indoor or outdoor applications [18–22,33–35] or with the effect of such a physical quantity on the thermal sensation [9–12], whereas any systematic study on the effect of the measurement method and/or the instrument on the thermal comfort (stress) assessment can be found.

To analyze in a definitive way the differences between the measurement carried out by different instruments and the role played by the mean radiant temperature measurement on the assessment of indoor thermal environments, in this paper will be showed the results of an experimental campaign carried out in a test room aimed to reproduce the typical microclimatic conditions (both in winter and in summer) of a moderate environment where the mean radiant temperature has been measured according to the mostly common methods and instruments reported by the ISO Standard 7726. Obtained results have been finally used to simulate how both accuracies and methods for the measurement of the mean radiant temperature can affect also the assessment of heat stress.

4. Experimental apparatus and methods

4.1. The room-test

To allow the comparison among the methods for the measurement of the mean radiant temperature a special test moderate environment has been built (Fig. 1). The wall exposed to West is fully windowed, the northern wall is adjacent to a room with characteristic similar to the test environment, whereas East and South walls are, respectively, adjacent to an access corridor and a stairwell, both controlled by the same HVAC system. In order to obtain seasonal microclimatic data with significantly different values of the mean radiant temperature in the test environment, a special system simulating the outdoor radiative contribution through the window both in summer and in winter has been also achieved. This system is made by a dummy-wall made by a thermostatic plate with a smaller surface area than the real window (0.16 m^2 instead of 7.6 m^2) placed in the test room in a such manner that the values of the angle factors of the sensors-panel and the sensors-window systems are the same.

The calculation of the angle factors required by the methods based on the contact temperatures and the infrared thermometer/thermal-camera (see Table 2) has been carried out according to formulas reported in ISO Standard 7726 [15] for a small plane element.

To review the typical mean radiant temperature measurement methodologies and verify their compatibility [25], different

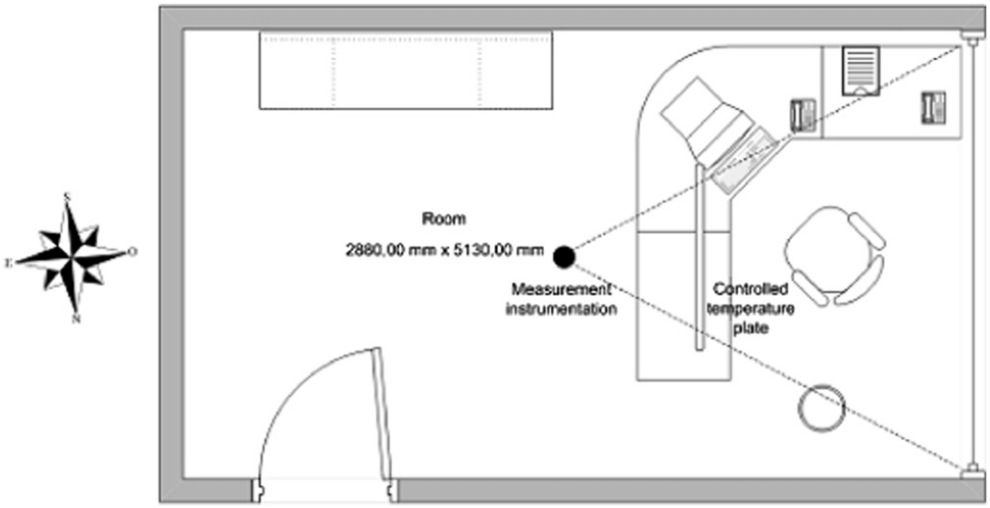

Fig. 1. Test room and experimental setup.

instruments with different accuracies were chosen on the market by the more common practice. All instruments are appropriated to respect the limit imposed by the ISO Standard 7726 [15]. The methods and instruments (whose specifications are reported in Table 3) for the measurement of the mean radiant compared in this investigation were as follows.

(i) The indirect method [1,15,33] based on the calculation of the angle factors and the measurement of the contact surface temperatures. In this case the measurements have carried out by means of several K-type thermocouples linked with a cold junction compensated data-logger, calibrated using a specific methodology [26].
(ii) The indirect method based on the calculation of the angle factors and the measurement of the surface temperatures by means of a remote infrared thermometer and a thermal-camera.
(iii) The direct method by using two commercial globes (labeled as globe 1 and globe 2) compliant with ISO Standard 7726 requirements [15] for application of class C (comfort);
(iv) The indirect method based on the measurement of the plane radiant temperatures. These measurements have been carried out by means of two different radiometers (labeled as net radiometer 1 and net radiometer 2) both compliant with ISO Standard 7726. In particular the former allows only a partial correction of the convective flow contribution (due to the presence of a capsule in polyethylene), whereas the second allows a full correction thanks to the presence of a further gold plate.

The direct method based on the globe was used as a reference because it is the most used and cheapest instrument (from the technical perspective) and easily traceable (from the theoretical perspective). The methods based on the two-spheres radiometer and the constant-air-temperature sensor have not been taken into account because the former is very hard to be obtained on the market and the second, although based on a user-friendly equipment, is suitable only for applications on a laboratory scale.

Finally, the measurement of the air temperature, the relative humidity and the air velocity have been carried out respectively by means of a dry bulb thermometer, a psychrometer and a hot-sphere anemometer all compliant with ISO 7726 requirements. These devices exhibited the typical metrological characteristics of the instruments used by skilled works personnel; in particular:

- the air temperature sensor exhibited accuracy and resolution values of 0.2 °C and 0.01 °C, respectively;
- the psychrometer exhibited accuracy and resolution values of 2% R.H. and 0.01% R.H., respectively;
- the hot-sphere anemometer showed repeatability and resolution values of 0.05 m $s^{-1}$and 0.01 m s^{-1}, respectively.

Table 3
Manufacturers specifications of instruments for mean radiant temperature measurement.

Measurement method	Sensor	Measurement range	Response time	Accuracy[a]
Indirect				
Angle factors with contact surface temperature	K-type thermocouples linked with a cold junction compensated data-logger	−40 to 375 °C	1 min	±1.5 °C
Angle factors with remote surface temperature	Thermal-camera	−40 to 500 °C	0.1 s	±0.04 °C (resolution), 320 × 240 pixel, 7.5–13 μm
	Infrared thermometer	0–100 °C	1 s	±0.1 °C (resolution)
Plane radiant temperature	Net Radiometer 1 (with polyethylene capsule)	$-50<\Delta t_{pr}<150$ °C	5 min (for 90%)	±0.2 °C (resolution)
	Net Radiometer 2 (with gold plate)	$-50<\Delta t_{pr}<50$ °C	1 min (for 90%)	±0.5 °C for $\|t_a - t_{pr}\| < 20$ °C ±0.5 °C + $1.5\|t_a - t_{pr} - 20\|/30$ for $\|t_a - t_{pr}\| < 50$ °C
Direct				
Globe temperature	Globe 1	5–100 °C	7 min (for 90%)	±0.5 °C for $5 < t_g < 50$ °C; ±1 °C for $50 < t_g < 100$ °C
	Globe 2	5–100 °C	7 min (for 90%)	±0.5 °C for $5 < t_g < 50$ °C; ±1 °C for $50 < t_g < 100$ °C

[a] The value of the accuracy is referred to the combined expanded measurement uncertainty [25].

Aiming to not affect each measurement by other meters or by the presence of the operators, the following precautions were considered: (i) the measurements with temperature contact probes and radiometers were automatically updated without operators; (ii) the plane radiant temperature probes were placed to avoid at all a mutual interference (or an interference with other probes); (iii) several measurements have been repeated under the same conditions by progressively placing the probes (e.g. the two globes); (iv) the measurements based on the thermal-camera were carried out by means of a mobile station removed after each measurement.

As each instrument showed a different response time (as shown in Table 3), each test was prolonged for at least 60 min continuously under steady-state conditions.

4.2. Moderate thermal environments assessment

The assessment of the global indoor comfort conditions has been carried out consistently with the common procedure worldwide accepted [36,37] for indoor thermal environments equipped with HVAC-systems [7,23,24] and based on the well-known Fanger's PMV index [1,2].

In particular, the calculation of the PMV index has been carried out by means of the TEE package [38], a special software devoted to the assessment of the Thermal Environment in agreement with all the International Standards in the field of the Ergonomics of the Thermal Environment.

The intrinsic clothing insulation values considered were those suggested by ISO 7730 for summer (0.5 clo) and winter (1.0 clo) clothing ensembles. According to ISO Standard 7730 [23] prior to calculate the PMV values, the intrinsic clothing insulation values have been corrected by the effect of body movements by means of special correlations as a function of the air velocity and the metabolic rate [39–41]. Finally, the reference value for the metabolic rate used for the assessment of thermal comfort conditions was equal to 1.4 met (typical for light activities [42]) (Table 4).

4.3. Hot environments assessment

To verify whether the incertitude related to the different method or probe used for the measurement of the mean radiant temperature affects the assessment also under hot conditions, the investigation has been extended also to the heat stress analysis by means of the PHS model [4,43,44]. In particular, as the test room has been designed to essentially reproduce microclimatic conditions typical of moderate environments, to induce the onset of heat stress, the analysis has been carried out by operating on the value of one or more parameters affecting the physiological thermal response predicted by PHS model. In particular the simulations have been carried out under two different conditions:

(1)By changing only the metabolic rate in the same room-test aiming to induce the onset of heat stress. The analyses have been carried out at three different levels of metabolic rate: 1.7 met (low), 2.8 met (moderate) and 4.0 met (high) according to ISO Standard 8996 [32,42] for an acclimatized subject.

(2)By changing both air temperature and relative humidity values keeping the same measured values of the mean radiant temperature and the air velocity. In the latest simulations the air temperature was increased of 5 °C and 10 °C with respect to the measured value and the relative humidity values have been changed to reproduce standard (RH = 50%), dry (RH = 30%) and humid (RH = 70%) conditions. In this case a low/moderate metabolic rate level (2.3 met) and a clothing insulation value typical for work clothes (1.0 clo) [45] have been considered (according to ISO Standard 9920 [45] mostly common work clothes exhibit a clothing insulation value over 0.6–0.8 clo).

5. Results and discussion

5.1. Measurements' implementation

The comparative investigation of the different measurement techniques discussed in this paper, has stressed the main peculiarities of each instrument from both the perspectives of their implementation and the metrological performance. Regarding the implementation, we can briefly summarize that:

- although the globe exhibit very high response time, is cheap reliable and user-friendly;
- the angle factor method coupled with contact thermometers, besides a difficult installation of the probes related to the contact resistances and a not easy implementation of the measurements, requires the calculation of the angle factor. On the contrary, by means of such a laboratory technique it is possible to measure even sudden changes of the mean radiant temperature than can occur in environments provided with large glass surfaces directly exposed to the solar radiation;
- the angle factor method assisted with the remote thermometers exhibits peculiarities similar to abovementioned even if it requires the assessment of emissivity of the surfaces. Anyway it is characterized by lower response times and an easier installation (the contact of the probe on the surface it is not required).

Table 4
Classification of the thermal environment for the comfort of the body as a whole and the local discomfort proposed by ISO 7730 [23] and EN 15251 [7] standards.

	ISO 7730					
	Category A		Category B		Category C	
	Condition	PD (%)	Condition	PD (%)	Condition	PD (%)
PMV	−0.20 to 0.20	≤6	−0.50 to 0.50	≤10	−0.70 to 0.70	≤15
$t_{a,1.1} - t_{a,0.1}$	<2 °C	≤3	<3 °C	≤5	<4 °C	≤10
$\Delta t_{(pr,0.6)h}$	<10 °C	≤5	<10 °C	≤5	<13 °C	≤10
$\Delta t_{(pr,0.6)v}$	<5 °C	≤5	<5 °C	≤5	<7 °C	≤10
v_a	DR <10	≤10	DR <10	≤10	DR <15	≤15
t_p	19–29 °C	≤10	19–29 °C	≤10	17–31 °C	≤15

	EN 15251							
	Category I		Category II		Category III		Category IV	
	Condition	PD (%)	Condition	PD (%)	Condition	PD (%)	Condition	PD (%)
PMV	−0.20 to 0.20	≤6	−0.50 to 0.50	≤10	−0.70 to 0.70	<15	<−0.70 or >0.70	>15

Table 5
Comparison between the mean radiant temperature values measured by means of different investigated methods. In the last column the differences with respect to the value chosen as reference have been reported.

Method	Quantity	Instrument	Mean measured value	Maximum SD of the directly measured quantity	SD of the indirectly measured quantity	Difference with respect to the reference instrument Δt (°C)
Plate at 10 °C						
Globe	t_r	Globe 1 (reference)	17.5 °C	0.03 °C	0.03 °C	–
		Globe 2	17.9 °C	0.03 °C	0.03 °C	+ 0.4
View factors		Thermocouples	17.5 °C	0.21 °C	0.03 °C	0.0
		Thermal-camera	17.3 °C	0.05 °C	0.05 °C	−0.2
		Infrared thermometer	18.3 °C	0.10 °C	0.10 °C	+ 0.8
		Net radiometer 1	21.8 °C	0.26 °C	0.16 °C	+ 4.3
		Net radiometer 2	18.0 °C	–	–	+ 0.5
t_{pr}	t_a	Dry bulb thermometer	19.9 °C	0.08 °C	–	
	Tu	Local turbulence intensity	43%	–	–	
	v_a	Anemometer	0.1 m s^{-1}	0.05 m s^{-1}	–	
	RH	Psychrometer	57%	2.10%	–	
Plate at 40 °C						
Globe	t_r	Globe 1 (reference)	21.3 °C	0.05 °C	0.05 °C	–
		Globe 2	21.8 °C	0.05 °C	0.05 °C	+ 0.5
View factors		Thermocouples	22.2 °C	0.80 °C	0.60 °C	+ 1.1
		Thermal-camera	22.7 °C	0.20 °C	0.05 °C	+ 1.4
		Infrared thermometer	22.7 °C	0.20 °C	0.10 °C	+ 1.4
t_{pr}		Net radiometer 1	26.8 °C	0.27 °C	0.18 °C	+ 4.3
		Net radiometer 2	22.0 °C	–	–	+ 0.7
	t_a	Dry bulb thermometer	21.7 °C	0.05 °C	–	
	Tu	Local turbulence intensity	40%	–	–	
	v_a	Anemometer	0.1 m s^{-1}	0.05 m s^{-1}	–	
	RH	Psychrometer	53%	2.00%	–	

The plane radiant method exhibits a very high sensitivity with respect to the convective phenomena around the probe (especially when a non-compensated probe is used). This is the only way to easily assess the radiant asymmetry in moderate environments [15,23,24].

5.2. Measurements' results

In Table 5 the results of the measurement of the mean radiant temperature carried out in the test room in Fig. 1 according to the abovementioned methods are reported. On the base of obtained results we can state that:

- the differences of t_r values measured by means of the investigated methods and instruments seem to increase as the mean radiant temperature increases. In all cases the values of the deviations Δt are within the range of the required accuracy asked by ISO Standard 7726 (apart from the net radiometer 1 which exhibits a deviation over the required accuracy value equal to 1 °C reported in Table 1).
- The methods based on the calculation of the angle factors and contact (or remote) surface temperature measurements appear in excellent agreement each other (especially at higher t_r values) and in a good agreement with the globe method (especially at low t_r values).
- Mainly due to the better spatial resolution of the method based on the thermal-camera and the possibility to adjust the emissivity of the measurement surface [46], at low mean radiant temperature the deviation between the reference value appears lower than that measured by means of the infrared thermometer.
- Using a net radiometer only partially compensated from the convective contribution resulted in an anomalous systematic difference (over than 4 °C) with respect to other instruments/methods both at low and high t_r values. This occurrence should suggest to avoid the use of such a device both under moderate and under severe environments because of the high sensitivity

Table 6
PMV values calculated according to the values of physical quantities reported in Table 5. $M = 1.4$ met. $I_{cl} = 0.5$ clo (1.0 clo) under summer (winter) conditions.

Device	t_o (°C)	PMV (−)	Class (ISO 7730)	Class (EN 15251)
Plate at 10 °C				
Globe 1 (reference)	18.7	−0.43	B	II
Globe 2	18.9	−0.40	B	II
Thermocouples	18.7	−0.43	B	II
Thermal-camera	18.6	−0.45	B	II
Infrared thermometer	19.1	−0.37	A	I
Net radiometer 1	20.9	−0.11	A	I
Net radiometer 2	19.0	−0.40	B	I
Plate at 40 °C				
Globe 1 (reference)	21.5	−1.05	–	II
Globe 2	21.8	−0.99	–	II
Thermocouples	22.0	−0.94	–	II
Thermal-camera	22.2	−0.89	–	II
Infrared thermometer	22.2	−0.89	–	II
Net radiometer 1	24.3	−0.40	B	I
Net radiometer 2	21.9	−0.97	–	II

Table 7
PMV mean sensitivity for both required and desired accuracy asked by ISO 7726 [15] to the mean radiant temperature for assessment carried out in summer and in winter season. $M = 1.4$ met; $I_{cl} = 0.50$ clo (1.0 clo) in summer (winter), $t_a = t_r$; $v_a = 0.1$ m s^{-1}.

PMV	ΔPMV			
	Required accuracy on t_r		Desired accuracy on t_r	
	Summer	Winter	Summer	Winter
−0.60	−0.23 to 0.24	−0.15 to 0.15	−0.02 to 0.03	−0.03 to 0.03
−0.35	−0.23 to 0.24	−0.15 to 0.15	−0.02 to 0.03	−0.03 to 0.03
0.00	−0.23 to 0.24	−0.15 to 0.16	−0.02 to 0.02	−0.03 to 0.03
+0.35	−0.23 to 0.25	−0.15 to 0.16	−0.02 to 0.03	−0.03 to 0.03
+0.60	−0.25 to 0.25	−0.15 to 0.16	−0.03 to 0.02	−0.03 to 0.03

Table 8
Mean radiant asymmetry values measured according to the different investigate methods/instruments.

Method	Sensor	Mean radiant asymmetry value, $\Delta t_{(pr,0.6)h}$, °C
Plate at 10 °C		
View factors	Thermocouples	1.9
	Thermal-camera	2.1
	Infrared thermometer	1.8
t_{pr}	Net radiometer 1	1.2
	Net radiometer 2	1.9
Plate at 40 °C		
View factors	Thermocouples	6.1
	Thermal-camera	6.5
	Infrared thermometer	5.3
t_{pr}	Net radiometer 1	2.7
	Net radiometer 2	6.0

of the radiative contribution of both comfort and stress indices [28,30,32].

5.3. The effect of measurement methods on the assessment of moderate thermal environments

Concerning the effect of the measurement method of the mean radiant temperature on the assessment of the comfort for the body as a whole, in Table 6 the PMV values under summer and winter conditions are reported. According to the PMV data consistent with the different values of the mean radiant temperature, it is almost astonishing how even little differences of t_r values result in very strong variations of the index. In particular, under winter conditions (plate at 10 °C), the PMV value varies of about three decimal points with the consequent impossibility of a reliable assessment of the environmental class (from B to A according to ISO 7730 Standard or II to I if the environment classification is made according to the recommended ranges of indoor temperatures reported in the EN Standard 15251). Even more surprising results have been obtained under summer condition. As a matter of fact, because of the high sensitivity of the radiative thermal flow with respect to t_r (according to the Stefan–Boltzmann's law the relationship is of the fourth order), the variation of the PMV index exceeded six decimal points. As a consequence, a reliable attribution of the class appears further complicated because the low air temperature value recorded into the test room (21.7 °C) under summer conditions promotes the shift of the PMV value toward slightly cool conditions (apart from the case when the mean radiant temperature was measured by means of the net radiometer 1).

As a consequence of the abovementioned sensitivity of the PMV index with respect to the different instrument/method used for the measurement of the mean radiant temperature, a reliable assessment of the thermal environment would seem almost impossible with the instruments actually available on the market [28]. In fact, according to very recent numerical findings of our team [28] obtained under similar conditions, a mean PMV deviation of about ±0.16 or ±0.25, respectively, was calculated within required accuracy asked by ISO 7726 (see Table 7). These evidences further confirm the crucial role played by the measurement of the mean radiant temperature in the assessment of the moderate thermal environment. The ambiguous assessment of the thermal sensation for the body as a whole as a consequence of the different methods/instruments is further confirmed by the values of the mean radiant asymmetry reported in Table 8. Obtained results clearly prove that the values of the asymmetries measured with the different investigated methods appear promoted at high temperature (plate at 40 °C) and inconsistent with the accuracy requirements asked by ISO Standard 7726 (see Table 1). Moreover, the values of the asymmetries calculated by means of the measurements of the contact temperatures appear consistent with those calculated by using the thermal-camera.

5.4. The effect of measurement methods on the assessment of hot thermal environments

The analyses carried out by means of the PHS model summarized in Table 9 reveal a quite negligible effect of the measurement instrument on the thermal stress assessment for both clothing insulation levels up to moderate metabolic rates. On the contrary, at high metabolic rates, the use of different instruments leads to an assessment not compliant each other, especially in the case of the

Table 9
Main physiological parameters and duration limit exposures predicted by means of PHS model according to the values reported in Table 5.

Instrument	M (met)	Final t_{re} (°C)		$D_{lim,tre}$ (min)		Water loss (g)		$D_{lim,loss}$ (min)	
		0.50 clo	1.0 clo	0.50 clo	1.0 clo	0.50 clo	1.0 clo	0.50 clo	1.0 clo
Globe 1 (reference)	1.7	37.2	37.2	>480	>480	654	1096	>480	>480
Globe 2		37.2	37.2	>480	>480	683	1121	>480	>480
Thermocouples		37.2	37.2	>480	>480	706	1141	>480	>480
Thermal-camera		37.2	37.2	>480	>480	735	1167	>480	>480
Infrared thermometer		37.2	37.2	>480	>480	735	1167	>480	>480
Net radiometer 1		37.2	37.2	>480	>480	986	1389	>480	>480
Net radiometer 2		37.2	37.2	>480	>480	694	1131	>480	>480
Globe 1 (reference)	2.8	37.5	37.5	>480	>480	2016	2737	>480	>480
Globe 2		37.5	37.5	>480	>480	2051	2774	>480	>480
Thermocouples		37.5	37.5	>480	>480	2079	2804	>480	>480
Thermal-camera		37.5	37.5	>480	>480	2114	2842	>480	>480
Infrared thermometer		37.5	37.5	>480	>480	2114	2842	>480	>480
Net radiometer 1		37.5	37.5	>480	>480	2420	3174	>480	>480
Net radiometer 2		37.5	37.5	>480	>480	2065	2789	>480	>480
Globe 1 (reference)	4.0	37.7	37.7	>480	>480	2839	*3840*	>480	470
Globe 2		37.7	37.7	>480	>480	2878	*3885*	>480	464
Thermocouples		37.7	37.7	>480	>480	2909	*3921*	>480	460
Thermal-camera		37.7	37.7	>480	>480	2948	*3968*	>480	455
Infrared thermometer		37.7	37.7	>480	>480	2948	*3968*	>480	455
Net radiometer 1		37.7	37.7	>480	>480	3288	*4377*	>480	414
Net radiometer 2		37.7	37.7	>480	>480	2893	*3903*	>480	462

Table 10
Main physiological parameters and duration limit exposures predicted by means of PHS by keeping the same Δt values in Table 5. $V_a = 0.1$ m s^{-1}, $M = 2.3$ met.

Instrument	Conditions	Final t_{re} (°C)	$D_{lim,tre}$ (min)	Water loss (g)	$D_{lim,loss}$ (min)
Globe 1 (reference)	$t_a = 26.7$ °C	37.4	>480	2299	>480
Globe 2	RH = 30%			2316	
Thermocouples				2343	
Thermal-camera				2377	
Infrared thermometer				2377	
Net radiometer 1				2680	
Net radiometer 2				2329	
Globe 1 (reference)	$t_a = 26.7$ °C	37.4	>480	2424	>480
Globe 2	RH = 50%			2464	
Thermocouples				2497	
Thermal-camera				2538	
Infrared thermometer				2538	
Net radiometer 1				2910	
Net radiometer 2				2480	
Globe 1 (reference)	$t_a = 26.7$ °C	37.4	>480	2762	>480
Globe 2	RH = 70%			2818	
Thermocouples				2865	
Thermal-camera				2924	
Infrared thermometer				2924	
Net radiometer 1				3478	
Net radiometer 2				2841	
Globe 1 (reference)	$t_a = 31.7$ °C	37.4	>480	2747	>480
Globe 2	RH = 30%			2788	
Thermocouples				2821	
Thermal-camera				2863	
Infrared thermometer				2863	
Net radiometer 1				3238	
Net radiometer 2				2780	
Globe 1 (reference)	$t_a = 31.7$ °C	37.4	480	3309	>480
Globe 2	RH = 50%			3375	
Thermocouples				3428	
Thermal-camera				3497	
Infrared thermometer				3497	
Net radiometer 1				4147	436
Net radiometer 2				3361	>480
Globe 1 (reference)	$t_a = 31.7$ °C	38.9	157	5232	331
Globe 2	RH = 70%	39.0	150	5342	323
Thermocouples		39.0	144	5432	316
Thermal-camera		39.1	139	5547	308
Infrared thermometer		39.1	139	5547	308
Net radiometer 1		39.8	105	6223	270
Net radiometer 2		38.9	151	5320	322

net radiometer (1) where the underestimation of the maximum duration of the exposure reaches a value of 46 min with respect to the reference globe. Similar results have been also found by changing the air temperature and the relative humidity (see Table 10); in particular for $t_a = 31.7$ °C the simulations returned a quite random assessment of the duration limit exposure especially at high relative humidity values (RH = 70%). It is noteworthy to stress that such results have been obtained on the basis of microclimatic conditions consistent with moderate environments (Table 5); as a consequence, to provide more realistic results, a further investigation in a special test room characterized by higher values of t_r and t_a consistent with hot workplaces (e.g. baking, glass factories, foundries, mines and so on) will be necessary.

6. Conclusions

This research has been completely devoted to the role of the measurement methods and the instruments needed for the measurement of the mean radiant temperature in moderate thermal environments. The experimental campaign carried out in a special test room aimed to reproduce the typical microclimatic conditions of moderate environments both in winter and in summer conditions, has stressed how a reliable assessment of the moderate thermal environments is actually impossible even if instruments are consistent with the accuracy requirements asked by International Standards. In particular the experimental results have highlighted the good reliability of the method based on the angle factors by using both radiation thermometers and thermal-camera. On the contrary, the method based on the net radiometer has resulted in measured values comparable with those exhibited by other techniques (globe included) only in the case of a full compensation of the convective contribution. The assessment of the thermal environment by means of PMV here reported has further revealed the highest sensitivity of such an index with respect to the choice of both sensor and methods. In particular, the deviation of the PMV value related to the use of a different sensor (from three to over six decimal point depending on the season) has exceeded the sensitivity of the index when the mean radiant temperature has changed within the accuracy requirements asked by ISO 7726 standard (from about two to about three decimal points depending on the season). As a consequence, a reliable attribution of the class of comfort becomes almost impossible.

The numerical results obtained by simulating hot stress conditions have revealed a certain randomness in the calculation of the limit duration of exposure requiring a further investigation under microclimatic conditions consistent with the onset of heat stress (higher air temperature and mean radiant temperatures under dry and hot conditions).

Finally, the authors believe that at the moment a thorough discussion focused on the measurements' protocols and the validation of standardized procedures of calibration is absolutely a must. Only by this way the role of other factors as the ability and the competence of the involved personnel will allow the reduction of their impact on the environment assessment. In a future work the analysis here reported will be extended also to: (i) different ambient geometries; (ii) different materials and different values of the emissivities of the surfaces; (iii) different climatic conditions; and (iv) hot and cold severe environments (Table 4).

Symbols [25,47]

D_{lim}	duration limit exposure, min
DR	draft risk, %
E_{eff}	effective radiant heat flow, W m^{-2}
$F_{p\text{-}i}$	angle factor between the person and the generic *i*-surface of the environment, N.D.
$h_{c,g}$	convective heat transfer coefficient of the black globe, W m^{-2} K^{-1}
I_{cl}	intrinsic clothing thermal insulation, clo
M	metabolic rate, W m^{-2} or met
P_b	heat supply to the black sensor in the two sphere radiometer, W m^{-2}
PD	percentage of dissatisfied, %
PHS	predicted heat strain model
PMV	predicted mean vote according to Fanger's theory, dimensionless
P_p	heat supply to the polished sensor in the two sphere radiometer, W m^{-2}
P_s	radiative flow exchanged by constant-air-temperature sensor, W m^{-2}
RH	relative humidity, %
SD	standard deviation of the measurement, °C
T_a	air temperature, K
T_b	reference body temperature, K
T_g	black globe temperature, K

T_i temperature of a generic i-surface of the environment, K
T_n temperature of the net radiometer, K
t_p floor temperature, °C
$T_{pr\text{-}i}$ plane radiant temperature with respect to the generic *i*-direction, K
t_o operative temperature, °C
T_r mean radiant temperature, K
t_{re} rectal temperature, °C
t_s temperature of a generic surface, °C
T_s temperature of the spheres or temperature of disc in two discs and net radiometer of the constant-air-temperature sensor, K
t_{sk} mean skin temperature, °C
Tu turbulence intensity, %
v_a air velocity, m s^{-1}

Greek letters
Δt difference of the current mean radiant temperature with respected to that measured by reference instrument, °C
$\Delta t_{(pr,0.6)h}$ horizontal radiant asymmetry measured at 0.6 m, °C
$\Delta t_{(pr,0.6)v}$ vertical radiant asymmetry measured at 0.6 m, °C
ε_b emissivity of the black sphere, N.D.
ε_g emissivity of the black globe, N.D.
ε_p emissivity of the polished sphere, N.D.
ε_s emissivity of the constant-air-temperature sensor, N.D.
σ Stefan–Boltzmann's constant, W m^{-2} K^{-4}

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