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Research Paper

Effects of radiant asymmetry on the thermal comfort conditions: Experiments in a test room

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ABSTRACT

Occupants' well-being in buildings is related to the thermal comfort conditions in indoor spaces. Radiant asymmetry is a parameter of localised discomfort and its evaluation is rather challenging. It should be considered when dealing with radiant systems since they could produce unacceptable asymmetric temperature fields. In this paper, the issue of radiant asymmetry in winter is experimentally investigated in a test room equipped with radiant panels. A first round of testing is carried out to study the limits in terms of supply water temperature of the heated surface in relation to the discomfort curves proposed in the current standards. Configurations with a heated wall or ceiling and the contemporary presence of one or more heat-dissipating surfaces are considered. Twelve scenarios representing real building situations are analysed, each involving three consecutive heating phases with increasing supply temperatures of 30, 35 and 40 °C. The most critical configuration is imposed in a second testing round with 8 participants checking the actual subjects' perceptions through questionnaires, with conditions of global thermal neutrality (PMV = 0). The scenario with a heated ceiling and heat-dissipating floor is the most adverse, generating a vertical asymmetry exceeding the standard limit of 4 °C when the supply temperature is above 35 °C. The survey campaign shows that uncomfortable cold sensations are prevalent with lower radiant asymmetry levels, whereas the highest ceiling temperature improves comfort perception. The results suggest that participants could not feel the asymmetry increment and analysis of radiant asymmetry discomfort should also consider surface temperatures along with plane radiant temperature difference.

1. Introduction

1.1. Background

Recent studies concerning buildings are focused on searching for new solutions for reaching high-quality indoor environments with low energy consumption [1]. Indoor comfort is a relevant aspect that affects people's well-being and it is widely investigated in the literature nowadays, especially if related to new and retrofitted buildings [2].

Ensuring high thermal comfort is a challenging goal only achievable if clear methodologies can assess targets for the indoor parameters and discomfort limits that should not be overcome. Their application is important for analysing conditions in existing buildings, for setting up the heating and cooling terminals, and especially for having guidelines for buildings and systems design phase [3].

Many different models were outlined over the years for thermal comfort analysis, but the most commonly used one was proposed by Fanger [4]. He conducted tests with 1300 participants, asking for their feedback in a test room used to reproduce different thermal environments. The outputs of the tests allowed the formulation of the PMV (predicted mean vote) and PPD (percentage of people dissatisfied) models, which indicate the rating of an indoor environment and the share of people who could express dissatisfaction using six inputs: the air temperature, the mean radiant temperature, the relative humidity, the air velocity, the metabolic rate and the clothing insulation. The current standard for thermal comfort investigations (ISO 7730) is based on Fanger's indexes and its use is applied for all the purposes mentioned above [5].

Together with the global comfort, Fanger collected in his book other factors that could act locally, causing local discomfort, independently from global perception. These factors are too hot or cold surfaces, which can lead to discomfort on contact, excessive vertical air temperature gradients between head and feet, high air velocities and asymmetrical radiant fields.

Achieving high standards of comfort in the building comes through careful selection and design of HVAC systems [6]. In this context, radiant panels are a promising solution for many reasons: first, they can

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Nomenclature

Shortcuts

TCV	Thermal comfort vote
TSV	Thermal sensation vote
Int	Intermediate questionnaire within the testing phase
Fin	Final questionnaire within the testing phase

List of symbols

$\Delta T_{p,r}$	Plane radiant temperature difference or radiant asymmetry [°C]
F_p	Angle factor [–]
T	Temperature [°C]
T_a	Air temperature [°C]
T_{mr}	Mean radiant temperature [°C]

Subscripts

bottom	Angle factor between the surface and the lower half-space
c	Cold
E	Angle factor between the surface and the half-space to the east
gl	Global
i	i-th surface
N	Angle factor between the surface and the half-space to the north
S	Angle factor between the surface and the half-space to the south
sup	Supply
top	Angle factor between the surface and the upper half-space
W	Angle factor between the surface and the half-space to the west
w	Warm
0.1 m	Sensor at 0.1 m height
0.6 m	Sensor at 0.6 m height
1.7 m	Sensor at 1.7 m height

easily be applied to new or retrofitted buildings; moreover, it has been widely demonstrated that their application involves a general increase in perceived thermal comfort [7]. For this reason, many works are analysing the issue of thermal comfort in rooms where radiant systems are installed [8]. However, in non-optimal sizing, some operating conditions could lead to local discomfort effects or energy wastes: some studies have recently focused on the analysis of radiant systems in intermittent heating, finding that radiant systems are not the best solution for this kind of operation [9]. For these reasons, clear guidelines on using radiant systems should be provided for more proper use, as suggested by Lim et al. in their paper [10]. One of the problems related to radiant panels can be the creation of asymmetric radiant fields and the consequent perception of radiant asymmetry due to improper operations [11]. In this case, one of the most relevant parameters measured to determine the radiative heat exchange, i.e., the mean radiant temperature (T_{mr}) can be hard to be measured, as defined in [12].

The calculation method for radiant asymmetry is defined by the ISO standard 7726 [13] and the limit values for discomfort are presented in ISO 7730 [5] and ASHRAE 55 [14]. The radiant asymmetry ($\Delta T_{p,r}$) is defined as “the difference between the plane radiant temperature of the opposite sides of a small plane element” [15] and it is therefore caused by a non-uniform radiant field. The plane radiant temperature ($T_{p,r}$) describes the thermal radiation in one direction. Its formulation is similar to the mean radiant temperature (T_{mr}), except for the angle factors, which, in the mean radiant temperature, describe the effect of radiation in all directions and are not bound to the plane orientation. Some authors have proposed more detailed methods for the evaluation of radiant asymmetry in enclosed spaces with a punctual spatial resolution [16,17].The above standards refer to the tests performed by Fanger in the ’80 s. At first, he studied the effect of the warm ceiling on thermal comfort: keeping a constant operative temperature – corresponding to neutral PMV – through the adjustment of the air temperature with an air change rate of 60 h^{-1}, he increased the ceiling temperature and, from subjects’ feedbacks and the assessment of 5 % of people dissatisfied as the limit for environmental design, he quantified to 4 °C the limit of $\Delta T_{p,r}$ for an acceptable environment in terms of radiant asymmetry discomfort for heated ceiling [18]. In his subsequent studies, applying the same methodology, he found the limits for the discomfort from a cool wall (10 °C), warm wall (23 °C) and cool ceiling (14 °C) [19].

After these findings, the approach to the discomfort caused by radiant asymmetry has changed. The literature review highlighted that recent works mainly deal with applying the standard’s methodology for verifying its validity and searching for new limits. In particular, Hodder et al. investigated a cooled room with a chilled ceiling and displacement ventilation. The ventilation rate was representative of real buildings (3 h^{-1}) and the top was cooled at different temperatures, corresponding to radiant asymmetry values up to 4 °C, keeping a thermally neutral environment (PMV = 0). The investigation did not show relevant novelties, as no discomfort for a cool ceiling was detected; however, it should be pointed out that the analysed radiant asymmetry range is almost limited ($\Delta T_{p,r}$ lower than 4 °C) for a configuration – cooled ceiling – that is rarely felt as uncomfortable [20]. Some years before, Berlung and Fobelets studied the effect of the combination of radiant asymmetry from a cold wall (between 0 and 20 K) and air velocity (between 0.05 and 0.5 m/s) in indoor spaces. The parametric study was performed for two indoor conditions: an operative temperature of a neutral environment and 3 °C below. The authors confirm the applicability of Fanger’s model and that draft and radiant asymmetry aspect are “independent and additive”. In the slightly cool condition, the acceptability is lower, as expected; however, it also drops with time and is higher at higher asymmetry, differently from what one might expect. Although the results were peculiar, the authors did not provide any comment [21]. On the same topic, in a more recent work published by Kalmár and Kalmár, a constant radiant asymmetry field of 6.53 K (corresponding to a warm wall with 31 °C surface temperature and an opposite cooled wall at 18 °C) was studied at varying air velocity, between 0.1 and 0.2 m/s. The change in air velocity involved a reduction in the PMV, initially 0 and decreasing to −0.45. The effect produced is a reduced localised heat and an enhanced localised cold sensation. Despite the drop in the thermal sensation vote (TSV), the acceptability of the environment does not seem affected by air velocity; the authors concluded that by increasing the air velocity, the perception of draught overwrites the asymmetry perception [22]. In general, the acceptability of the environment is quite elevated; in fact, such a value for warm/cool walls seldom causes discomfort in room occupants. Dong e al. investigated the effect of solar radiation on comfort conditions in a room equipped with radiant heating panels. The horizontal radiant asymmetry at head level raised up to 4 °C, compared to the scenario without solar radiation. However, the room was heated by multiple radiant surfaces and standards don’t provide limit curves for the analysed configuration [23].

Other works tried to apply the method developed by Fanger to explore further limits for discomfort from radiant asymmetry. Zhou et al. proposed curves for discomfort from radiant asymmetry due to a cooled floor [24]. They investigated the effect of exposure time on the acceptability of the environment, evaluating the different results between 8 h and 2 h tests creating different asymmetric environments with radiant systems on the floor and ceiling, with realistic ventilation rates (180 m^3/h, corresponding to 5 h^{-1}). The tests were performed at PMV = 0; however, as expressed by Fanger in [19] referring to the works of Griffiths and McIntyre [25], the simultaneous cooling and heating of opposite surfaces could create conditions that are not representative of real environments. Although very interesting, the approach proposed by Zhou et al. seems to investigate temperatures beyond the operation limits (the cooled floor at T < 19 °C). Su et al. explored the percentage of dissatisfied (PD) for radiant asymmetry caused by a cold wall at a distance of 1 m. They tested the presence of uniformity and two radiant asymmetry levels (ΔT_{pr} = 0 °C; 2.1 °C; 4.1 °C). In these cases, the environment was in cool conditions (T_{mr} ϵ [16.5, 18.6], T_{air} ϵ [17.2, 18.8]), and authors asked participants to adjust their clothes in the first 30 min (they reached clothing values between 1.25 and 1.40 clo) to reach neutrality. The acceptability curve was stricter than Fanger's [26]. The approach observed in this last article has been widely used in recent years: the effect of radiant asymmetry is studied in the winter season, using a cool environment as a reference. For this reason, the acceptability curves are, in all cases, very different and difficult to compare with the existing literature. Su et al. analysed the effect of exposure distance to exterior wall/window in a room heated through radiators or floor heating. The authors found a limit of ΔT_{pr} according to the participants' feedback; however, it is not clear whether the discomfort is caused by the radiant asymmetry, whose value is very limited (below 3.7 °C), or by the cool environment (T_{air} ϵ [18.5, 19.1]) [27]. The same conclusions can be obtained by reading the work by Wang et al., where the radiant asymmetry caused by a heated panel is investigated in different room positions. It is difficult to generalise the results of this paper for many reasons: the operative temperature ranges were quite important in various cases and positions in the room. Moreover, the ΔT_{pr} studied was just in a narrow range (between 0 and 2 °C, limits not causing discomfort asymmetry in hot panel case). Another aspect is the definition of the asymmetric thermal sensation vote (ATSV) that could give information about the participants' perception of radiant asymmetry, but it suggests that participants were aware the topic of the research was the discomfort from asymmetric fields, and their awareness could affect the feedback [28].

The limit of these approaches is that testing environmentally critical conditions can take to answers hard to be explained: almost all the participants experienced low acceptability and comfort in the environment, but it is impossible to state the cause. These studies were proposed to investigate the effect of radiant asymmetry on real environments, but this is not always an effective method. Zhou et al. applied the knowledge acquired in test room experiments on a real office building, and they found new curves for the acceptability of a room cooled with a radiant floor. The authors state the difficulty of controlling environmental factors and the non-uniform environment in on-field studies, aspects that make the findings difficult to generalise [29]. The same issue could be discussed about the paper of Su et al. [30]. The authors conducted on-field measurements in classrooms and offices, finding various operative temperatures and participant feedback. Their analysis of the global comfort inside the analysed environments is interesting, but their approach to the study of the effect of radiant asymmetry due to a cold wall cannot be generalised for many reasons: first of all, the co-presence of a cold window and hot radiator in the same surface tend to mitigate the calculated radiant asymmetry, but it is not possible to know whether this attenuation also happens for the occupants; moreover, it is not possible to state if the discrepancy between the answers to the comfort and the sensation votes are to be attributed to radiant asymmetry, especially in such a uniform environment.

1.2. Aim and novelty

In this paper, the problem of radiant asymmetry is experimentally addressed in a test room equipped with radiant surfaces. The methodology adopted in this work differs from most of the articles found in the literature and presented in the previous section. They mainly focus on the asymmetry caused by warm or cold surfaces without debating the reproduced environment's verisimilitude. The premises of this work are the same as Safizadeh et al. [31], i.e., to reproduce realistic environments to investigate whether the radiant asymmetry could cause discomfort in these places. However, compared to their paper, in this work, the approach was inferred from the Standard ISO 7730 [32], minimizing the global discomfort (i.e., setting PMV = 0) and analysing the effect of local discomfort by increasing asymmetry levels. The PMV model was chosen for the room set-up as it is used by the Standard to define indoor thermal comfort and because the paper aims at typical sizing and design conditions and the null PMV is easily recognized as a reference condition for HVAC systems' design. The flexibility of the test room used for the experimental campaign and described in [33] enables to investigate the effect of realistic environmental conditions on human thermal perceptions. In particular, the activity looks at the potential discomfort caused by a heated surface in winter, and the objective is twofold. Firstly, the limits for warm surface and water supply temperatures are investigated based on the discomfort curves proposed by the current standards. In the experimental campaign, the presence of one or more heat dissipating surfaces is considered, generating different radiant asymmetric fields that could represent real building situations. The obtained results could support engineers in the designing phase of radiant systems. Subsequently, a survey campaign is carried out with real participants implementing the most critical scenario, given by the warm ceiling configuration, and checking people's actual perceptions towards the imposed thermal environment. This work reports an exploratory activity and is aimed at a preliminary estimation of the investigated topics, that will be further explored with a larger sample in future works. In the present paper, the proposed tests try to reproduce real temperature fields leading to realistic conditions of radiant asymmetry, an aspect almost missing in the literature. The aim is to assess if the adopted methodology can be effectively applied in future tests dealing with the issue of radiant asymmetry. In addition, a first hint on the importance of considering radiant asymmetry in the panel's sizing is provided, and the gathered experimental data can give a contribution in this sense.

2. Methods

This section presents the methodology applied in this work. First, the experimental facility, the CORE-CARE laboratory, is offered [33]. Then, the experimental approach, organised into two test sessions, is explained. The first one reproduces various indoor environmental conditions with different radiant fields to look for design limits for radiant panels in a scenario of retrofit action, according to the current standards. The latter investigates the presence of people inside the environment to check if the limit conditions according to current standards are uncomfortable.

2.1. Experimental facility: The CORE-CARE laboratory

The CORE-CARE laboratory is a test room built at the Department of Industrial Engineering of the University of Padova. It is the result of converting a space previously used as an office; the walls were further insulated, and radiant panels were applied on each room surface, controllable in heating or cooling mode. The radiant floor is an embedded system, whereas prefabricated plasterboard panels are installed on all the other surfaces. The dynamic response of each radiant surface has been assessed both in heating and cooling regime in a previous work [33]. The test room's dimensions are 4.6 × 4 × 2.8 m, and one wall – with two windows – borders the outside; the room is equipped for reproducing an office environment where people can perform a sedentary activity. All the surfaces can heat or cool the room independently; a mechanical ventilation system provides a fresh outdoor air flow rate between 80 and 250 m^3/h. The laboratory has a control room where hot and cold water production occurs. The set points for hot and cold water tanks are 45 °C and 10 °C, the limit temperatures for the radiant systems' operations. In the test room, 31 sensors are used to detect the surface temperature of the radiant surfaces and the windows (4 sensors for each surface, 1 sensor for each window), the air temperature at 4 different heights (0.1 m, 0.6 m, 1.1 m, 1.7 m), the relative humidity and the CO_2 concentration inside the room. The logging system stores data from all the sensors with a 2 s timestep. In this work, the focus is on the thermal conditions created inside the test room; however, the envelope and the materials affect how these conditions are created and reached. To have an insight on this aspect, the further description of the laboratory with the materials of the surfaces, stratigraphy, sensors' technical specifications and other technical information on the test room can be found in [33].

2.2. The first round of testing without participants

The first test series aimed at searching for surface temperature limits to avoid indoor discomfort from radiant asymmetry, according to the ISO 7730 standard guidelines. To reach this goal, the CORE-CARE laboratory was used to reproduce a room with radiant panels supplied by hot water in various positions and working with different supply temperatures. Thanks to the adopted plant, different combinations with variable numbers and positions of heat dissipating walls were reproduced in this room. In the following paragraphs, the term "heat dissipating wall/surface" will indicate the replication of external surfaces by cooling them down at 18 °C. Once reached the equilibrium with the surfaces, three water supply temperatures were tested for the heated surface, i.e., 30 °C, 35 °C, and 40 °C, in sequence. For each supply temperature set (from here on called "phases"), the test lasted about 1.5 h to enable the radiant surfaces and air to reach stable conditions; when this condition was fulfilled (i.e., the surface temperature difference between successive timesteps for all the surfaces lower than 0.1 °C), the average air temperature (T_a), mean radiant temperature (T_{mr}) in the centre of the room at a height of 0.6 m (Eq. (1) and radiant asymmetry (ΔT_{pr}) (Eq. (2) at the same height were calculated. The height of 0.6 m corresponds to the centre of a seated person, and this choice was made consistent with the activity performed by the participants in the second test.

$$T_{mr} = \sum_i T_i F_{p_i} \quad (1)$$

$$\Delta T_{pr,AB} = T_{pr,A} - T_{pr,B} \quad (2)$$

For the calculation of ΔT_{pr}, subscripts A and B represent the two opposite orientations (i.e., the direction of a vector normal to the surface) of the plane used for the calculation. For all the analysed scenarios, the radiant asymmetry was calculated in the vertical direction at 0.6 m height ($\Delta T_{pr,vert}$), in the horizontal direction between east and west ($\Delta T_{pr,EW}$) and between north and south ($\Delta T_{pr,NS}$), always with a plane cutting the room into two halves (see Fig. 1). The angle factors (F_p), calculated with the software TRISFE [34], are shown in Table 1.

2.2.1. Analysed scenarios

In this work, 12 scenarios were investigated, and the tests were performed between February 7 and 17, 2022. Two main heating systems were considered, i.e., warm ceiling and wall. For each case, the combination of adjacent and opposite heat dissipating walls, floor, or ceiling was supposed, and each scenario was reproduced with the three different hot water supply temperatures (phases). The air temperature was not controlled in these tests and the mechanical ventilation system was switched off. A summary of the scenarios is shown in Table 2.

2.2.2. Test structure

The tests layout is shown in Fig. 2. After switching on the detection system, the circulation pump of the heat dissipating surfaces was activated at 17 °C supply temperature; it was observed that, with this setting, the surface temperature of the walls in one hour reached 18 °C. After the cooled surface had stabilised, the warm surface was supplied with hot water, in increasing steps, at 30 °C, 35 °C and 40 °C, respectively. Each hot surface setting was kept for about 1.5 h: immediately after the setting changes, the dynamics of the radiant surface worked to reach steady conditions (30–45 min); after that time, the average temperatures were calculated for the remaining time (45–60 min) until the next set change.

The test layout shows that in the proposed experimental approach, the control is only performed manually on the surface temperature feedback, acting on the water supply temperature. The water flow rate was kept constant; furthermore, the operative and air temperatures were monitored, but no action was planned to control them, as, in this phase, there were no occupants in the room.

2.3. The second round of testing with participants

Among all the scenarios, it was decided to choose the most critical and representative of a real-life case to investigate whether the analysed limits for thermal discomfort due to radiant asymmetry are effectively perceived as such; hence, experimental sessions with two participants each were planned. The tests were scheduled in 5 winter days, between December 6 and 23, 2022. Since the lab external wall is East-oriented, and it is significantly shaded by other buildings on that side, the solar

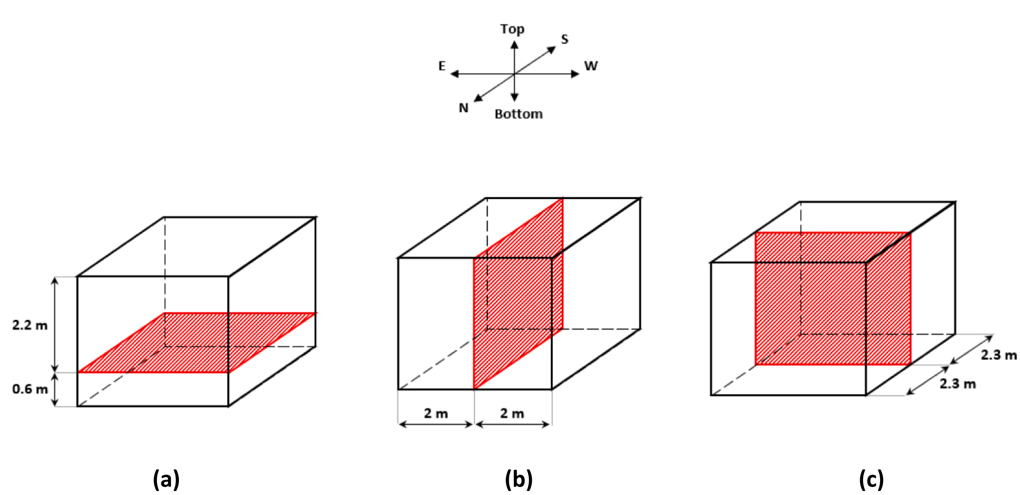

Fig. 1. Plane position and orientation for the calculation of radiant asymmetry in the vertical direction (a), E-W direction (b) and N-S direction (c).

Table 1
Angle factors (F_p) used for calculating the T_{pr} in the centre of the room at 0.6 m (first column). All the other columns report angle factors on half-spaces ($F_{p,i}$) for radiant asymmetry calculation (see nomenclature for the subscripts meaning).

Surface	F_p	$F_{p,bottom}$	$F_{p,top}$	$F_{p,N}$	$F_{p,S}$	$F_{p,E}$	$F_{p,W}$
North Wall	0.1014	0.0532	0.1496	0.2028	0	0.1014	0.1014
West Wall	0.1322	0.0718	0.1926	0.1322	0.1322	0	0.2644
South Wall	0.1014	0.0532	0.1496	0	0.2028	0.1014	0.1014
Windows	0.0284	0	0.0568	0.0284	0.0284	0.0568	0
East Wall (no windows)	0.1038	0.0718	0.1358	0.1038	0.1038	0.2076	0
Ceiling	0.1578	0	0.3156	0.1578	0.1578	0.1578	0.1578
Floor	0.3750	0.75	0	0.3750	0.3750	0.3750	0.3750

Table 2
Settings for each analysed case (H = heated surface; D = heat dissipating surface).

N° Test	Case study	Day	Analysed setting					
			West Wall	East Wall	North Wall	South Wall	Ceiling	Floor
Test 1	1.1	07 Feb.	H	D				
	1.2	08 Feb.	H	D				D
	1.3	08 Feb.	H	D			D	
Test 2	2.1	14 Feb.		D		H		
	2.2	14 Feb.		D		H		D
	2.3	15 Feb.		D		H	D	
Test 3	3.1	09 Feb.					H	D
	3.2	10 Feb.		D			H	D
	3.3	10 Feb.		D	D		H	D
Test 4	4.1	17 Feb.		D	D	H		
	4.2	16 Feb.		D	D	H		D
	4.3	15 Feb.		D	D	H	D	

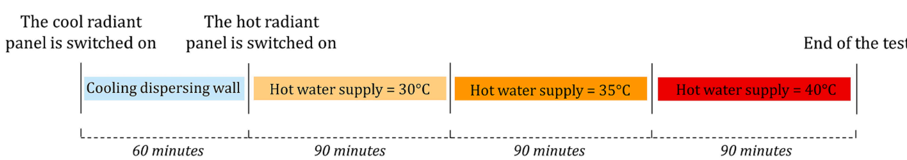

Fig. 2. Timeline of the tests without occupants.

radiation level was low. The sample was composed of 8 students, aged between 22 and 29, 7 males and 1 female; all reported to be in good health and to have had no relevant physical activity in the hours before the test. They were engaged in sedentary activity (i.e., metabolism equal to 1.2 met) during the whole test and answered a questionnaire at regular time intervals, whose responses were used to evaluate the perceived discomfort. The tests were performed with fixed clothing with a thermal resistance equal to approximately 1 clo (the detail of the clothing resistance calculation is provided in Appendix C). The same condition analysed in the previous session was reproduced: the floor was cooled, controlling the surface temperature to reach 18 °C, and the three supply hot water temperatures were set for the ceiling heating. In these tests, the real-time PMV was calculated through the measurements performed by the lab's sensors and the supply air was adjusted at each phase to keep the indoor environment thermally neutral (i.e., PMV = 0).

2.3.1. *Test's layout*

For each test, two people were expected to participate in the trial. However, in two planned tests, one of the participants was absent, and the test was performed with one person. During the preparation phase, a thermal dummy (180 W) was introduced in the test room to simulate two occupants and the first asymmetrical condition was reproduced: the adjustment of air temperature was carried out, and after reaching a steady condition, the participants were introduced to the room while taking out the thermal dummy. In Fig. 3, the test is described.

When participants entered the laboratory, they were asked to answer a questionnaire on personal data about their names, ages, gender, weight, height and physical activity before the tests. Regarding the perception of the thermal environment during the different tested conditions, a questionnaire was filled out in the middle and at the end of each phase. The presence of the two tests contributes to analysing the variation in time of perception by the occupants. Although not reported in the timeline, the participants were allowed to leave the room for a break between the second and the third test phases due to the length of the test session. Once entered again in the room, the last phase's timeline was the same as the first one: 30 min for the acclimation and 90 min for the testing part, in which an intermediate questionnaire was filled in after 45 min and the final questionnaire at the end.

The questionnaire, reported in Tab. A1 (Appendix A), was built according to Standard ISO 10551 [35]. It was split into different parts: at

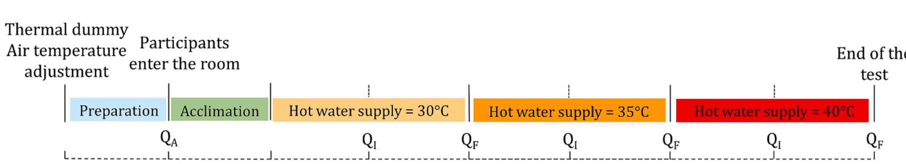

Fig. 3. Timeline of the tests with occupants and questionnaires (Q_A: questionnaire for personal data, Q_I: intermediate questionnaire, Q_F: final questionnaire).

the beginning, the global thermal perception and evaluation were asked, then questions about the localised warm and cool sensation and the associated comfort were investigated. Finally, questions about the perception of smell and feedback about the air quality were asked, but the results did not give relevant elements and were not reported in this work. The global and local comfort perceived by participants were analysed through the Thermal Sensation Vote (TSV) and Thermal Comfort Vote (TCV). The TSV was only used for the description of the global thermal perception, whereas the TCV was used for the description of the global thermal evaluation (TCV_{gl}), the evaluation related to the localised cold (TCV_c) and warm (TCV_w) perceptions. A graphical representation of the scales used in this work is shown in Fig. 4.

As a choice for applying the method, it was decided not to give indications to the participants, unaware of tests being carried out.

3. Results and discussion

The results of this work deal with the supply temperature limits for space heating. Although these values cannot be generalised, they offer an overview of the design of a wide range of buildings. In the second test phase, the effective perception of participants was checked in an asymmetric environment, and their feelings were analysed.

3.1. The first round of tests

The calculated radiant asymmetry (Eq. (2) is reported for each investigated solution in Figs. 5-8. In particular, Fig. 5 outlines the results for the scenario of a heated wall and an opposite heat dissipating wall, Fig. 6 shows the results for a heated wall and an adjacent heat dissipating wall, in Fig. 7, the results of heated ceiling and heat dissipating floor are shown, finally, in Fig. 8 there are the results for a heated wall with adjacent and opposite heat dissipating walls. In Fig. 7, two "variations" to the original scenario are presented, with one or two additional heat dissipating walls together with the floor; in the other figures, the two "variations" consist of an additional heat dissipating floor or ceiling.

Comparing the tests' results with the standard for the radiant temperature asymmetry (which defines the asymmetry limits of 23 °C for the warm wall and 4 °C for the warm ceiling), it can be deduced that the only configurations that may lead to an exceedance of the limit imposed by regulations are those concerning the installation of a radiant ceiling for space heating in the scenario a cold floor with 40 °C supply temperature, with cold floor and one cold surface with 35 and 40 °C supply temperature and with cold floor and two cold surfaces with 35 and 40 °C supply temperature, as it can be seen in Fig. 7.

Considering the asymmetry created by radiant walls, higher values are reached when considering their installation opposite to the heat dissipating surface (Fig. 5). The asymmetry on a vertically oriented plane facing the involved surfaces ($\Delta T_{pr,EW}$) assumes high values (around 4 °C in case of 40 °C supply water temperature) and, whether the floor is at low temperature (in this case at 18 °C), the vertical asymmetry reaches values between 2 and 3 °C. Despite being far from the standard discomfort limits, it cannot be claimed that the reproduced environment does not result in discomfort, given the simultaneous presence of vertical and horizontal asymmetry. On the other hand, the configuration with adjacent warm and cold surfaces (Fig. 6), and those with both an opposite and adjacent outdoor wall (Fig. 8), result in lower radiant asymmetry levels.

In the case of a heated ceiling, in the first supply water temperature step (30 °C), the value of $\Delta T_{pr,vert}$ is slightly below 4 °C, but most tested configurations exceed the comfort limits in the higher supply temperature scenarios. The maximum value for vertical radiant asymmetry reached in the tests was detected with heat dissipating wall and floor, and it is equal to 6 °C, corresponding to 7 % PD, according to [5]. The values for horizontal asymmetry showed that levels are very low. In Table 3, the results for each analysed scenario are reported.

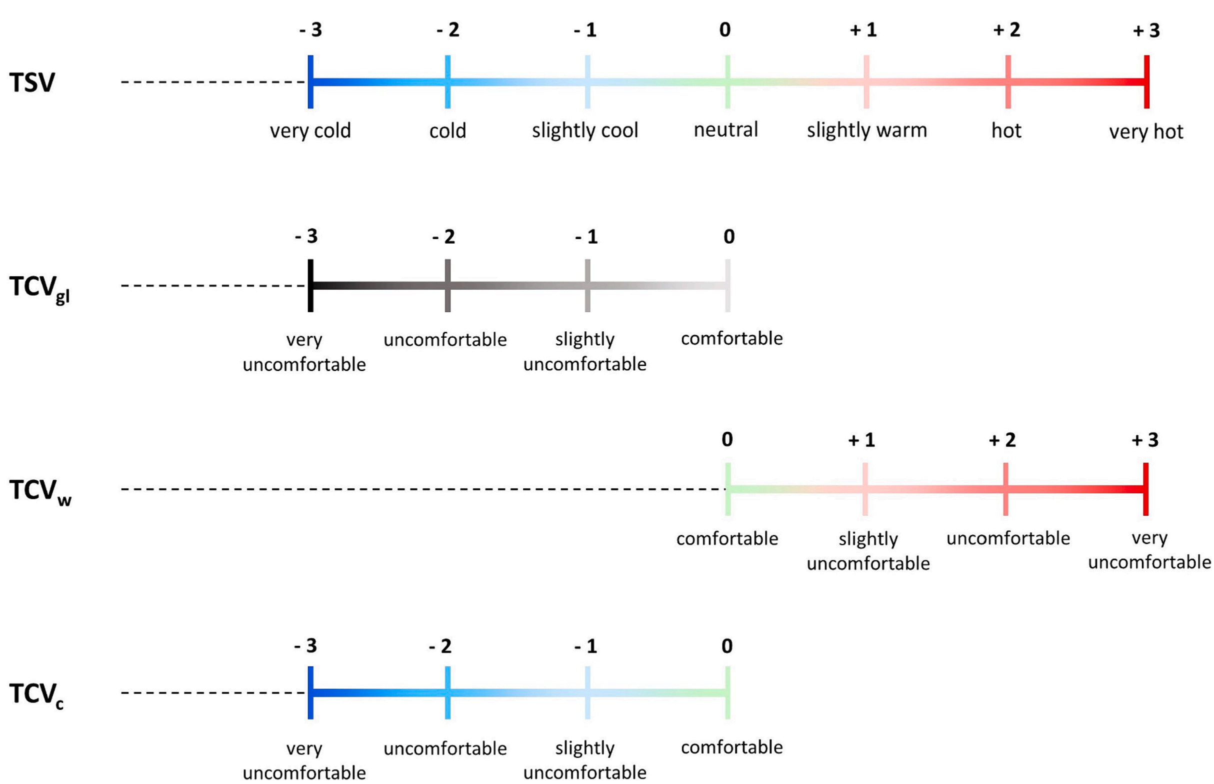

Fig. 4. Scales used for evaluating the thermal sensation vote (TSV), global thermal comfort vote (TCV_{gl}) and thermal comfort vote due to localised warm (TCV_w) and cold (TCV_c) sensations.

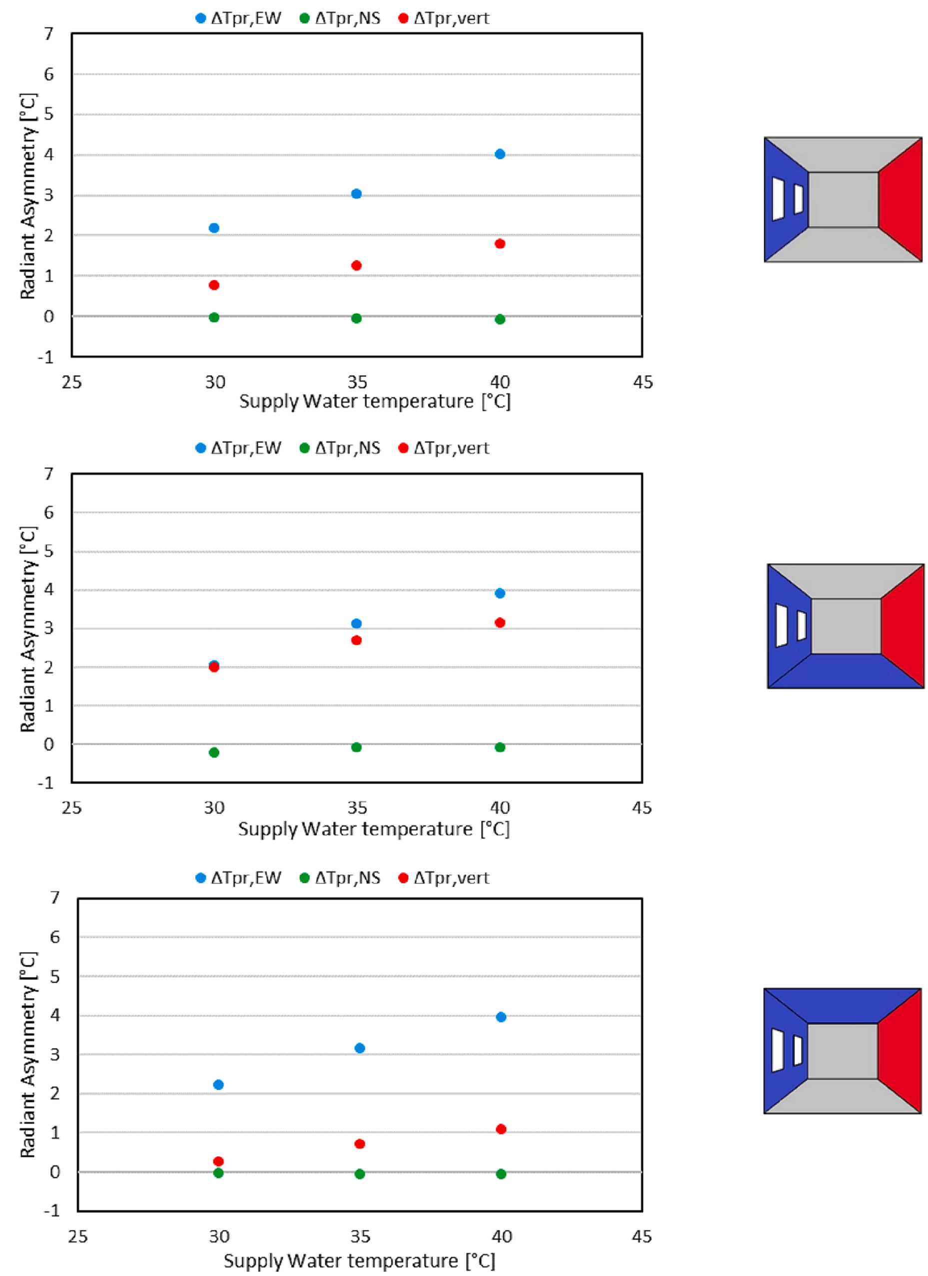

Fig. 5. Radiant asymmetry evaluated for test 1: heated wall and opposite heat dissipating wall. The figure on the right of each graph outlines the analysed scenario, with the heated (red) and heat dissipating (blue) surfaces.

3.2. The second round of tests

From the analysis of the results of the first test session, it was decided to investigate the most critical case, i.e., CASE 3.1, with the presence of occupants. During the tests, the environmental parameters were measured; the obtained profile for each test is shown in Fig. 9. Each graph represents the measured values for one of the performed tests. The variations of the parameters along the phases are reported, with the measured radiant asymmetry (blue line), the air temperature (purple line), the mean radiant temperature (green line) and the operative temperature (red line) profiles. The time the questionnaires were filled is also shown in every graph (orange marker at the bottom). To better visualize the room's detailed dynamics, the reader can refer to Fig. B1 in Appendix B, which reports the temperature profiles of the indoor air, the passive and active surfaces for one of the test sessions.

In the proposed test setting, the room conditions are controlled through the walls' surface temperatures, and it is not possible to directly act on the T_{mr} to reach a thermally neutral condition. In almost all the tests, the T_{mr} presents a value not sufficient for reaching indoor thermal neutrality during the first phase (i.e., when the supply water temperature of the radiant ceiling is 30 °C). In this first part, the ventilation system was set with a high supply temperature (i.e., around 30 °C), resulting in an indoor environment with higher T_a, but lower T_{mr}. In the second phase (supply water temperature equal to 35 °C), the observed T_{mr} is higher, leading to the possibility of supplying air at a lower temperature compared to the previous phase as the mean radiant temperature is high enough to keep a 0 PMV; as a consequence, an almost uniform environment is obtained, with similar values for T_a and T_{mr}. Finally, in the third phase (with supply water temperature at 40 °C), the air temperature is used to cool down the air inside the room and offset all the loads. As can be observed in Fig. 9, the behaviour of the room is similar in all the tests, as it can be controlled with high precision.

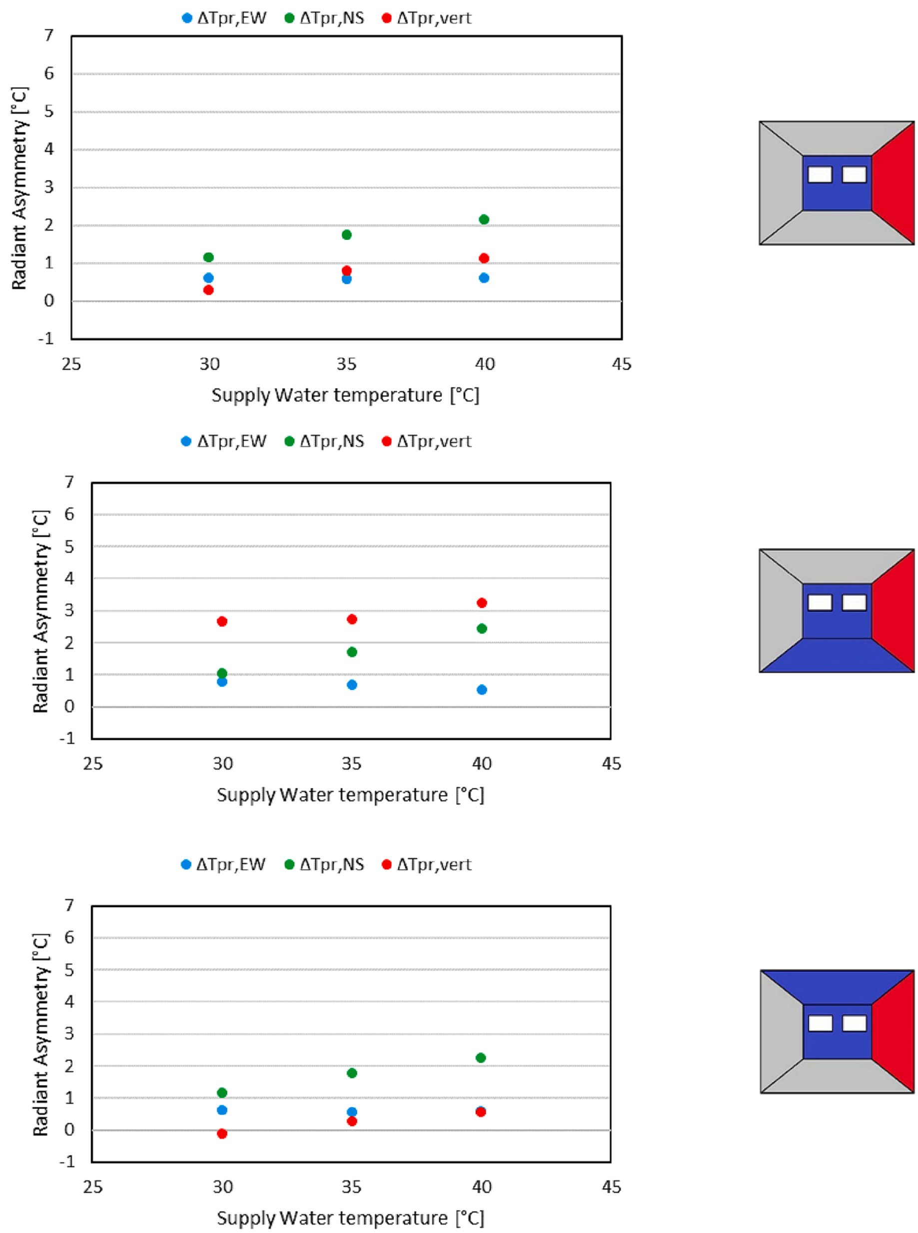

Fig. 6. Radiant asymmetry evaluated for test 2: heated wall and adjacent heat dissipating wall. The figure on the right of each graph outlines the analysed scenario, with the heated (red) and heat dissipating (blue) surfaces.

The profiles of the vertical radiant asymmetry $\Delta T_{pr,vert}$ shown in Fig. 9 are calculated through Eq. (2) from measured surface temperatures and angle factors (Tab. 1). Six time instants were considered for a more effective analysis of the results, corresponding to the moment the questionnaires were filled. The ΔT_{pr} calculated in all 5 tests are grouped for each timing and reported in Fig. 10. Three radiant asymmetry levels were reproduced in the tests: the average values of the calculated ΔT_{pr} are around 4.3 °C, 5.1 °C and 6.4 °C in the three hot water supply temperature scenarios and they are very similar between the intermediate (“Int”) and final (“Fin”) questionnaires.

Observing all the tests (Fig. 9), it can be noted that the purpose of keeping a quite constant operative temperature was reached, as in all the tests, its fluctuations are limited. The value is also very similar in the different tests, as the temperature for thermal neutrality was very close. To guarantee minimum variations of the PMV, around zero, the air temperature was gradually lowered over the test duration, as the T_{mr} increases for the ceiling temperature rise. Hence, in all the tests, similar conditions were reproduced with constant T_{op}, changing T_{mr} and T_{air} over the test duration.

The survey participants’ feedback is shown after being converted to votes in Fig. 11, according to the scales shown in Fig. 4. Comparing Fig. 11(a) (referred to global perception) and Fig. 11(b) (on local comfort votes), some interesting aspects can be observed. The similarity between the TSV, TCV_{gl} and TCV_c profiles shows that when present (mainly in the first and second phases), the localised cold perception is relevant and causes low TSVs and slight discomfort in participants. On the contrary, a higher comfort level is found in the highest ceiling temperature scenario: the analysis of the answers to the localised sensations shows that the warm feeling increases with the ceiling temperature. It is mainly perceived at the head level but, in some cases, also in the feet and chest/back. However, as shown in Fig. 11(b), only in a few cases the warm feeling is evaluated as uncomfortable: the feedback reported during the surveys’ filling highlights a contained value of TCV_w. The cold localised perception is mainly perceived at lower ceiling temperatures and is limited in the scenario with the highest ceiling temperature. The perception is concentrated in the extremities, such as feet,

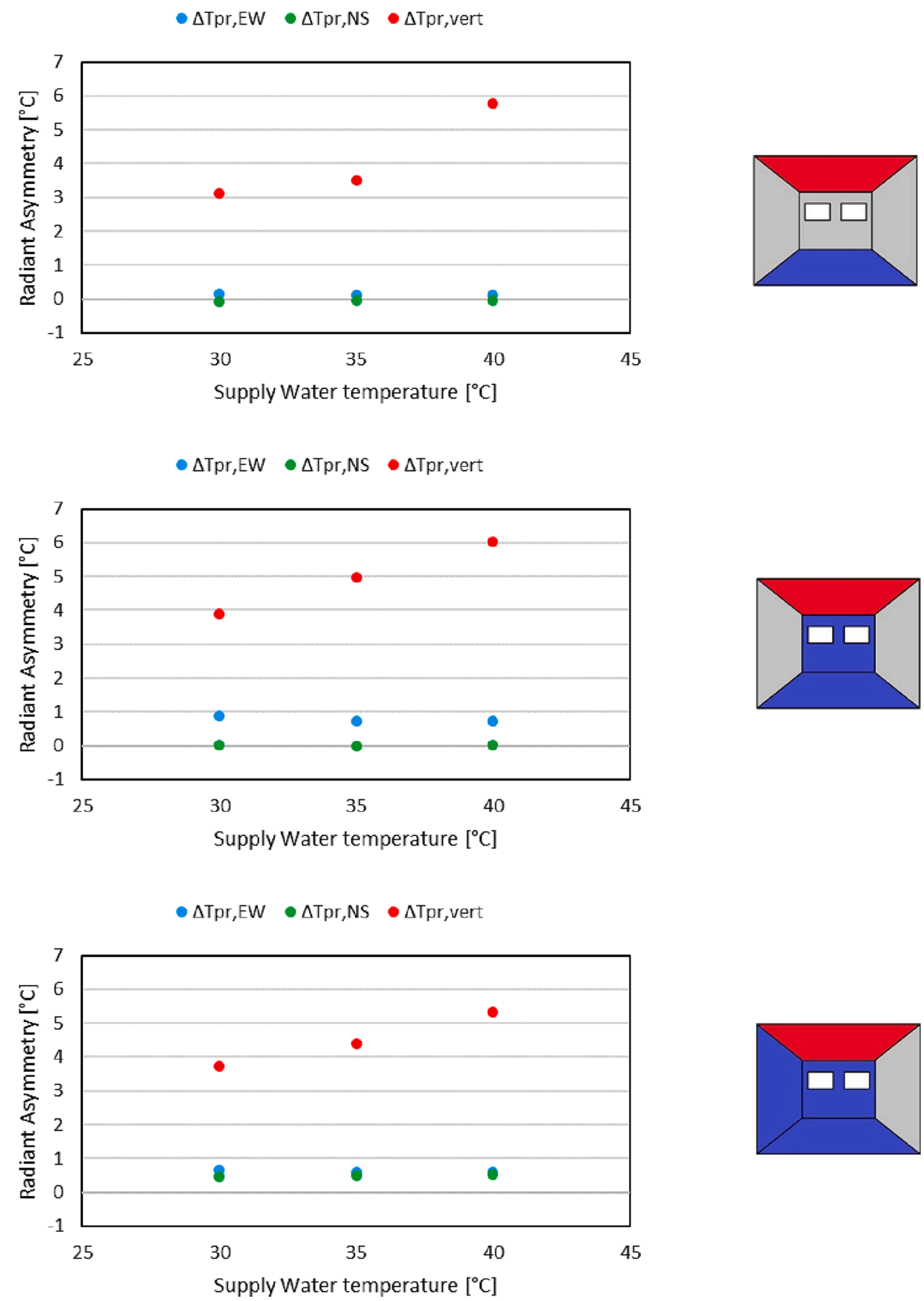

Fig. 7. Radiant asymmetry evaluated for test 3: heated ceiling and heat dissipating floor. The figure on the right of each graph outlines the analysed scenario, with the heated (red) and heat dissipating (blue) surfaces.

hands and arms; differently from the warm sensation, it generally causes slight discomfort in the participants.

Observing the TSV and TCV_{gl} in the first and second supply temperature sets (30 and 35 °C, respectively), it can be noted that the sensation and comfort perceptions decrease until the 2nd phase intermediate (“2 Int”) survey is filled. After this part, both votes increase and stabilise around zero for the third phase (“3 Int” and “3 Fin”). When filling out the “2 Int” survey, participants have been in the room for 2 h with the first case setting and the supply ceiling temperature has been increased to 35 °C for the last 45 min. Different aspects could be the cause of the observed variability in the feedback: the acclimation seems to play an important role, as in almost all the observed cases, at the beginning of the tests, participants reported a decreasing perception, although in a room with constant parameters for 2 h (e.g., comparing the TSV and TCV_c between the intermediate and final surveys in the 1st test phase). Another aspect could be related to the short-term thermal behaviour of the participants subjected to transient conditions. However, this aspect has not been explored much and should be analysed more deeply. The TSV is caused by the localised cold sensation (TCV_c), which affects the global comfort of participants, while the discomfort due to the warm feeling seems not to have a relevant impact. The third setting, where a higher level of radiant asymmetry is experienced, seems less critical, as participants report no particular levels of global or local discomfort.

From these results, it seems that different factors act on the people participating in the tests: the time of exposure to a certain condition and the acclimation have an important effect. To keep a constant T_{op} in the first part of the tests, the air temperature T_a is higher than the mean radiant temperature T_{mr}, whereas in the final part the T_{mr} is dominant; it should be suggested that the unbalancing of these two temperatures –

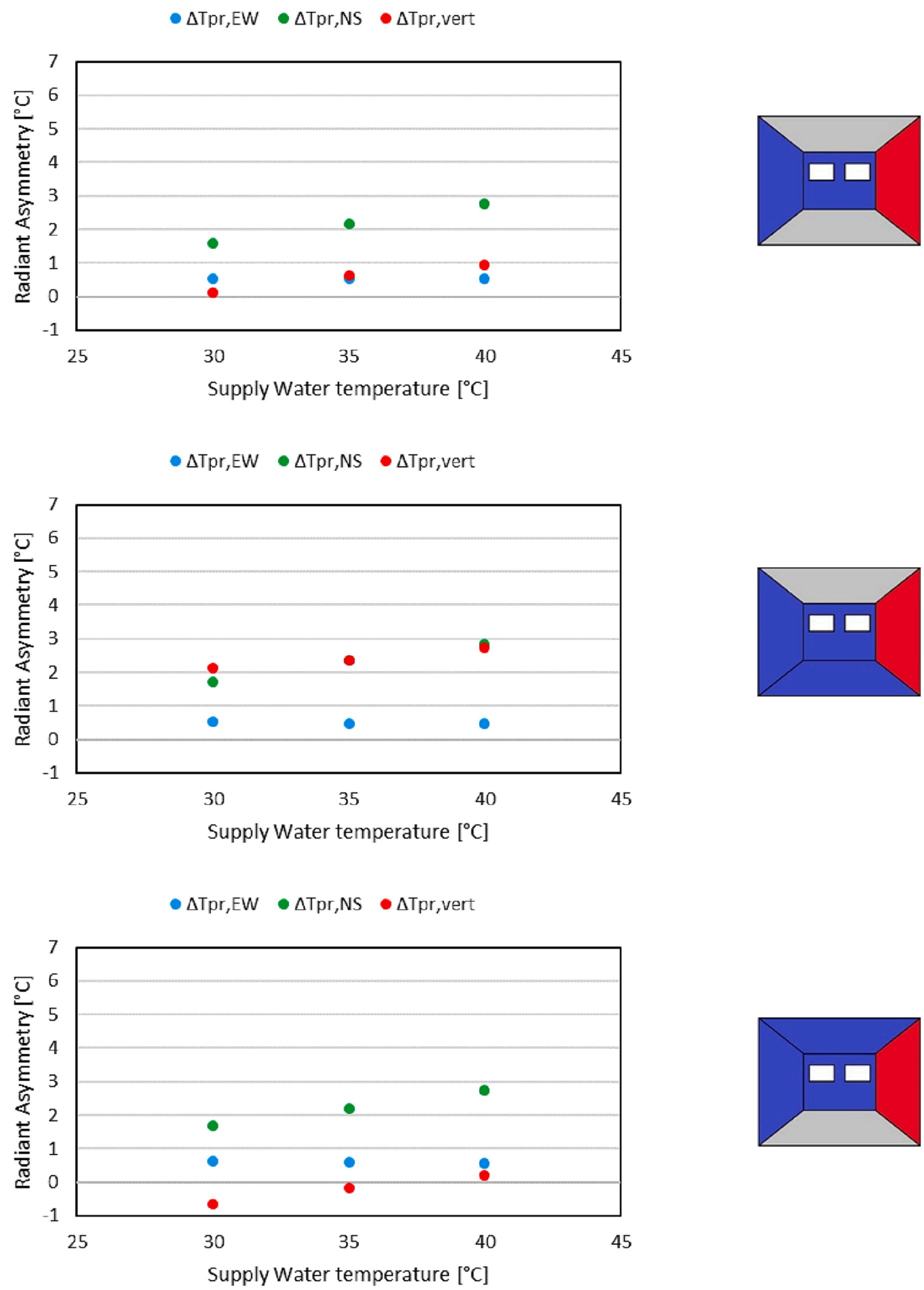

Fig. 8. Radiant asymmetry evaluated for test 4: heated wall with adjacent and opposite heat dissipating wall. The figure on the right of each graph outlines the analysed scenario, with the heated (red) and heat dissipating (blue) surfaces.

Table 3
Vertical radiant asymmetry for each tested case with a warm ceiling. Values in bold are beyond the limit for ISO 7730 [5].

	T_{sup} [°C]	$\Delta T_{pr,vert}$ [°C]
CASE 3.1	30	3.1
(warm ceiling – heat dissipating floor)	35	3.5
	40	**5.8**
CASE 3.2	30	3.9
(warm ceiling – heat dissipating floor and 1 wall)	35	**5.0**
	40	**6.0**
CASE 3.3	30	3.7
(warm ceiling – heat dissipating floor and 2 walls)	35	**4.4**
	40	**5.3**

and the associated differences in convective and radiant heat exchange – affects people's perception and comfort. In any case, it was noted that participants were not aware of the radiant asymmetry; more, this factor seems not to cause them discomfort; indeed, in the highest asymmetry level (ΔT_{pr} = 6.4 °C), higher comfort ratings were found.

In the first and second phases, the discomfort perception could be linked to the cool floor or the air at a low level. For this reason, two more parameters were monitored, as these usually cause local discomfort perception: air vertical temperature gradients and floor surface temperature. In Fig. 12, the air temperature difference between ankles and neck is reported (it is obtained through the difference between the temperature detected at 1.7 m height and that at 0.1 m) together with the floor surface temperature. The limit proposed by the Standard ASHRAE 55 [14] for avoiding discomfort due to vertical air gradients (1.76 K/m, corresponding to a 3 °C difference between ankle and neck) has never been reached in these tests. Despite a higher variability of

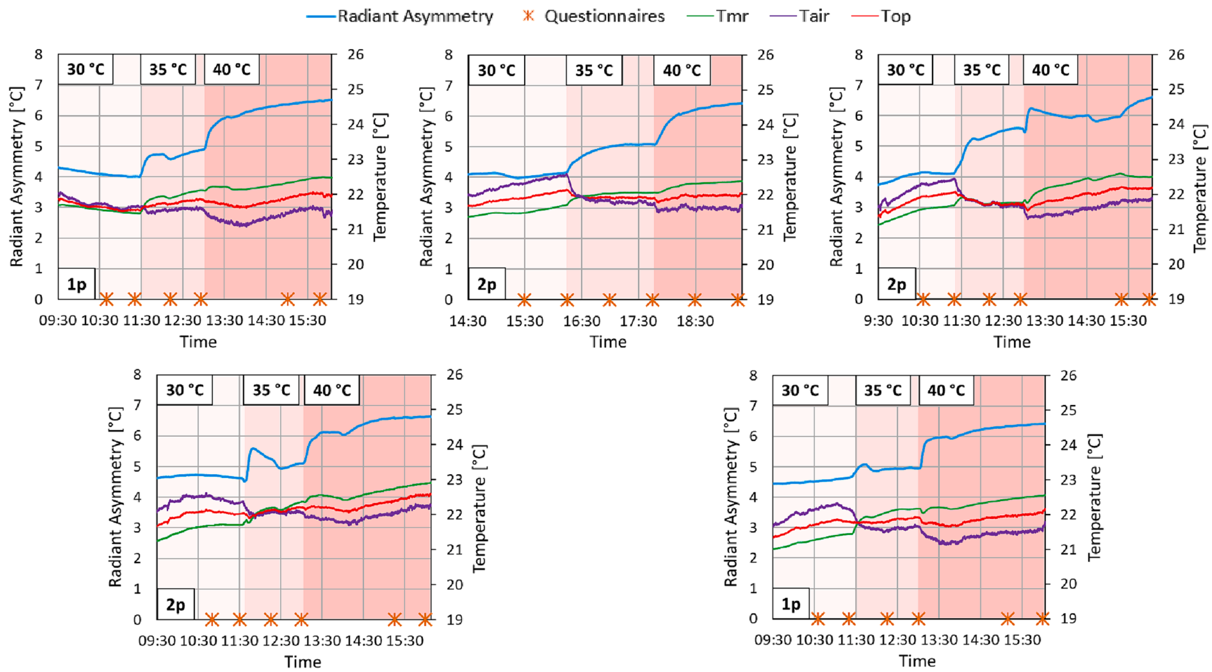

Fig. 9. Environmental parameters measured during the performed tests. The label at the bottom left corner on each graph specifies if the test was performed with one participant (1p) or two participants (2p), the labels at the top report the water supply temperature in the corresponding test phase.

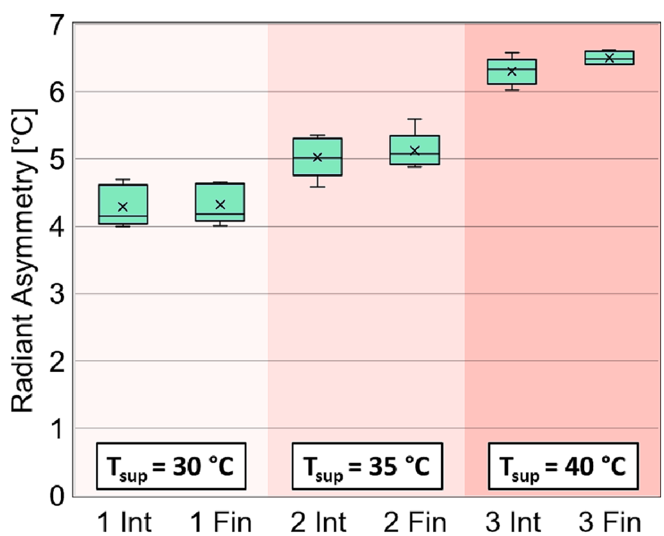

Fig. 10. Calculated radiant asymmetry in all the tests during the surveys' filling. "Int" and "Fin" refer to the intermediate and final questionnaires, respectively.

vertical gradients in the first scenario, it can be assumed that conditions are similar along the tests for air temperature gradients and floor surface temperatures. At the same time, the air temperature at 0.1 m was monitored, and its value was found to be in the range of 20.8 ± 0.5 °C for all the phases and tests.

The similar conditions of floor surface temperature and vertical air temperature difference in all the tests confirm that the variability of the feedback shown in Fig. 11 is not due to these aspects. Rather, it seems that participants are affected by the cold floor when the ceiling does not counterbalance, that is when the ceiling temperature, T_{mr} and, consequently, the radiation heat transfer from the ceiling are lower. On the other side, the radiation heat transfer from the floor does not change along the test, as the surface temperature is constant.

In conclusion, the tests show that the comfort perception in a real building with vertical radiant asymmetry needs to be evaluated in depth. Participants seem to be affected by acclimation and transient room conditions; at the same time, the analysed sample seems not to be aware of the increasing asymmetry level or does not perceive discomfort at values of ΔT_{pr} defined as "out of comfort range" by the current Standards. For all the mentioned reasons, further studies should be conducted with a wider sample to analyse each factor's possible influence on people's perception and comfort in such an asymmetric environment.

4. Conclusions

In this work, the discomfort caused by radiant asymmetry in indoor environments has been analysed. In particular, using a test room, different scenarios were investigated, representing realistic indoor environments with radiant panels used for heating and heat dissipating surfaces in different positions. This approach, in which people are tested in realistic asymmetric controlled environments rather than uniform environments with warm or cold surfaces, has limited matches in the literature. Some measurements were performed focusing on the limit of radiant asymmetry provided by the standards, with the following findings:

- The most critical configuration deals with a heated ceiling and a heat dissipating floor; with a supply temperature higher than 35 °C, there is the risk of exceeding the 4 °C limit declared by the standard.

These results can be useful in the design phase of radiant ceiling systems, as they associate the supply water temperature to the radiant asymmetry value in some configurations, highlighting the configurations potentially exceeding the limit.

The same scenario was studied with 8 people seated in the room where asymmetric conditions were created. The operative temperature was almost constant throughout the test and corresponded to a PMV equal to zero. Three increasing asymmetry levels were created and the occupants' feedback highlighted that:

- The participants could not perceive the increase in radiant asymmetry.

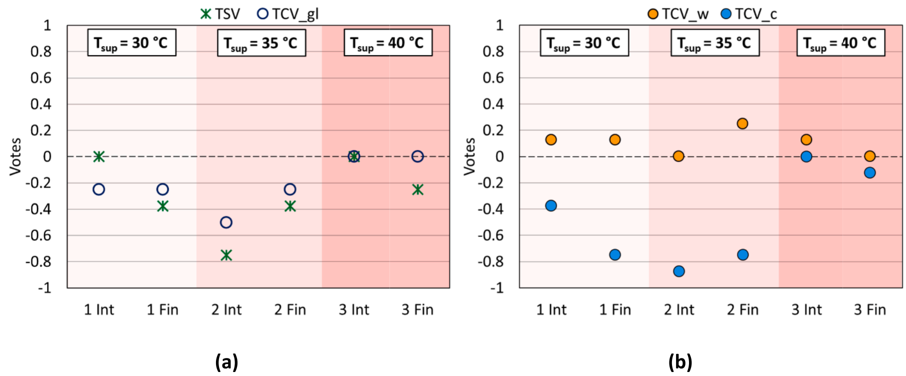

Fig. 11. Global thermal sensation and evaluation (a) and local thermal comfort vote for cold and warm body parts (b) obtained by the survey answers. "Int" and "Fin" refer to the intermediate and final questionnaires, respectively.

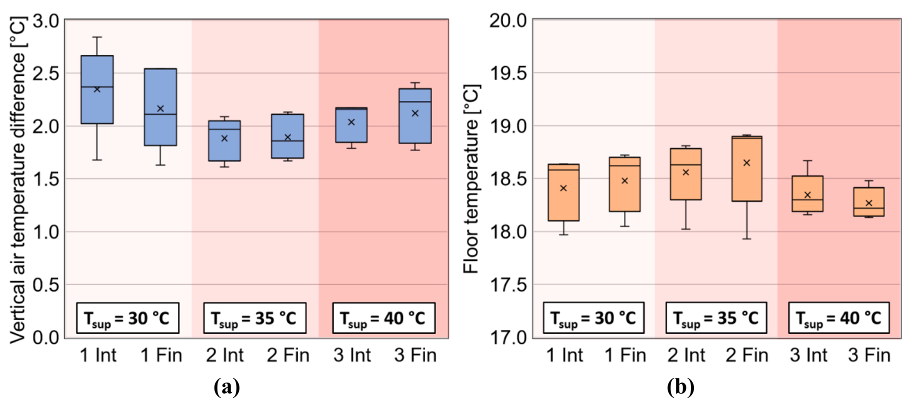

Fig. 12. Vertical air temperature difference between ankles and neck (a) and floor surface temperature (b) in all the tests' phases. "Int" and "Fin" refer to the intermediate and final questionnaires, respectively.

- The cold localised sensation was prevalent, despite the neutral PMV; in most cases, it caused discomfort.
- The warm localised sensation increased with the ceiling temperature but rarely caused discomfort; differently from expected, the higher ceiling temperature (which corresponded to the higher asymmetry levels) involved a higher comfort perceived by occupants.

The main limitation of this work concerns the low number of participants in the test. For this reason, rather than conclusive findings, the obtained results can provide a preliminary insight into the radiant panels' operation range in a realistic environment when accounting for the potential discomfort caused by thermal asymmetry to occupants. The methodology showed interesting preliminary outcomes, and its application in future works might lead to interesting results. Another limitation deals with the age of the participants: in future work, it might be interesting to investigate the effect of participants' age on radiant asymmetry perception. The aspects that have never been considered in the analysis of discomfort from radiant asymmetry are the evaluation of the different contributions of convective and radiant heat exchange between the indoor environment and the occupants; moreover, in the evaluation of radiant asymmetry, the focus on temperatures, together with ΔT_{pr}, could give more information and explain what is not understood yet.

CRediT authorship contribution statement

Marco Marigo: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Giacomo Tognon:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Michele De Carli:** Funding acquisition. **Angelo Zarrella:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendices.

Appendix A. – Questionnaire for thermal comfort and radiant asymmetry assessment

In Tab. A1 are shown the questions from the surveys administered to the participants in each test carried out during the research for the evaluation of thermal perception and evaluation of global and localised comfort. The test was administered in English, so the questions presented here are part of the original questionnaire and not a translation.

Table A1: Questionnaire for assessing global and localised thermal sensation and evaluation.

Questionnaire: global and localised thermal sensation and evaluation
In this questionnaire, you are asked simple questions about your current thermal sensations and your perception of indoor air quality.
Read carefully the descriptions and indications under the questions, if present.
1. Please, indicate your workstation
■ CORE-CARE 1
■ CORE-CARE 2
1 — Evaluation of Global Comfort
In this section, you are asked to evaluate your global thermal sensation. Mark the appropriate box about your current perception.
1. How do you feel at this precise moment?
■ Very cold
■ Cold
■ Slightly cool
■ Neither cold nor hot (neutral)
■ Slightly warm
■ Hot
■ Very hot
■ I don't know / I can't define it
2. Do you find this feeling…?
■ Comfortable
■ Slightly uncomfortable
■ Uncomfortable
■ Extremely uncomfortable
2 — Evaluation of Local Comfort — Warm sensation
In this section, you are asked to say if you feel any sensation of local thermal discomfort (warm sensation).
1. Do you feel hot or warm in one or more specific parts of the body?
■ Yes *(Go to question 3.1)*
■ No *(Go to question 4.1)*
3 — Evaluation of Local Comfort — Warm sensation on specific points of the body
In this section, you are asked to specify in which parts of the body you perceive a warm sensation.
1. In which one/ones do you feel a hot/warm sensation? *(you can select more than one option)*
If other parts of the body than those listed are included, mark the last box and indicate them as follows:
part1/ part2/ etc…
■ Head/Face
■ Neck/Back of the head
■ Chest
■ Back
■ Arms
■ Hands
■ Thighs/Legs above knees
■ Calves/Legs below knees
■ Ankles/Feet
■ Other (*specify*): ………………………….
2. How do you feel that/those part/parts of the body in this precise moment?
– If you indicated one item in question 1, mark one of the first three boxes.
– If you indicated two or more items in question 1, and you have the same feelings, mark one of the first three boxes.
– If you indicated two or more items in question 1 and you have different feelings, mark the fourth box and specify for each part the thermal sensation separated by a slash as follows:
part1: slightly warm/ part2: very hot/ part3: hot/ etc…
■ Slightly warm
■ Hot
■ Very hot
■ Other (*specify*): ………………………….
3. Do you find this feeling…?
– If you indicated one item in question 1, mark one of the first three boxes.
– If you indicated two or more items in question 1, and you have the same feelings, mark one of the first three boxes.
– If you indicated two or more items in question 1 and you have different feelings, mark the fifth box and specify for each part the perceived feelings separated by a slash as follows:
part1: comfortable/ part2: uncomfortable/ part3: slightly uncomfortable/ etc…
■ Comfortable
■ Slightly uncomfortable
■ Uncomfortable
■ Extremely uncomfortable
■ Other (*specify*): ………………………….
4 — Evaluation of Local Comfort — Cool sensation
In this section, you are asked to say if you feel any sensation of local thermal discomfort (cool sensation).

(*continued on next page*)

(*continued*)

Questionnaire: global and localised thermal sensation and evaluation
1. Do you feel cold or cool in one or more parts of the body? ■ Yes *(Go to question 5.1)* ■ No *(Go to question 6.1)*
5 — Evaluation of Local Comfort — Cool sensation on specific points of the body
In this section, you are asked to specify in which parts of the body you perceive a cool sensation.
1. In which one/ones do you feel a cold/cool sensation? *(you can select more than one option)*
If other parts of the body than those listed are included, mark the last box and indicate them as follows:
***part1/ part2/ etc**…*
■ Head/Face ■ Neck/Back of the head ■ Chest ■ Back ■ Arms ■ Hands ■ Thighs/Legs above knees ■ Calves/Legs below knees ■ Ankles/Feet ■ Other (*specify*): ………………………….
2. How do you feel that/those part/parts of the body in this precise moment?
– If you indicated one item in question 1, mark one of the first three boxes.
– If you indicated two or more items in question 1, and you have the same feelings, mark one of the first three boxes.
– If you indicated two or more items in question 1 and you have different feelings, mark the fourth box and specify for each part the thermal sensation separated by a slash as follows:
***part1: slightly cool/ part2: very cold/ part3: cold/ etc**…*
■ Slightly cool ■ Cold ■ Very cold ■ Other (*specify*): ………………………….
3. Do you find this feeling…?
– If you indicated one item in question 1, mark one of the first three boxes.
– If you indicated two or more items in question 1, and you have the same feelings, mark one of the first three boxes.
– If you indicated two or more items in question 1 and you have different feelings, mark the fifth box and specify for each part the perceived feeling separated by a slash as follows:
***part1: comfortable/ part2: uncomfortable/ part3: slightly uncomfortable/ etc**…*
■ Comfortable ■ Slightly uncomfortable ■ Uncomfortable ■ Extremely uncomfortable ■ Other (*specify*): ………………………….
6 — Evaluation of the Indoor Air Quality
In this section, you are asked to say how you find the quality of indoor air.
1. Do you find the air to be…? ■ Fresh ■ Slightly stuffy ■ Stuffy ■ Very stuffy
2. Do you find the air smelly? ■ Yes ■ No
3. Referring to your answer to question 6.1, how would you define indoor air? ■ Clearly acceptable ■ Acceptable ■ Just acceptable ■ Just unacceptable ■ Clearly unacceptable

Appendix B. – Detailed measurement of environmental variables

In this section, the detailed measurements performed during one of the test sessions are provided, for a better understanding of the dynamics of the environment. The test carried out on December 14, 2022, was reported as it was considered representative of all tests performed in this phase of the trial. In Fig. B1, the dynamic profile of the temperatures inside the CORE-CARE laboratory are shown. The difference between active and passive surfaces can be clearly distinguished; moreover, it can be noted that the air temperature is in equilibrium with the passive surfaces for the whole test duration. Except from the phase changes indicated in the graph, all the other temperature changes (i.e., the ceiling and floor temperature variations), are related to the control of the water supply temperature.

Surface	F_p	$F_{p,bottom}$	$F_{p,top}$	$F_{p,N}$	$F_{p,S}$	$F_{p,E}$	$F_{p,W}$
North Wall	0.1014	0.0532	0.1496	0.2028	0	0.1014	0.1014
West Wall	0.1322	0.0718	0.1926	0.1322	0.1322	0	0.2644
South Wall	0.1014	0.0532	0.1496	0	0.2028	0.1014	0.1014
Windows	0.0284	0	0.0568	0.0284	0.0284	0.0568	0
East Wall (no windows)	0.1038	0.0718	0.1358	0.1038	0.1038	0.2076	0
Ceiling	0.1578	0	0.3156	0.1578	0.1578	0.1578	0.1578
Floor	0.3750	0.75	0	0.3750	0.3750	0.3750	0.3750

Fig. B1. Dynamic profile of the temperature of active and passive surfaces and indoor air during the test performed on December 14, 2022.

Appendix C. – Detailed calculation of the clothing resistance

In this section, the detailed calculation of the clothing resistance for the test sessions is provided. All the tests were performed with fixed clothing resistance, the participants were contacted in advance asking them to wear a typical, but specific, winter clothing. The clothing resistance was calculated in advance using the Annex C of the ISO 7730 Standard. They were asked to wear usual underwear (about 0.03 clo), a T-shirt (about 0.09 clo), winter socks that covers the ankles (about 0.05 clo), shoes (about 0.04 clo), trousers (about 0.25 clo), a long-sleeve sweatshirt (not present in the standard, but comparable to a thick sweater, about 0.35 clo). The sum of the clothing resistance of these garments, equal to about 0.81 clo, was added with the resistance of an executive chair (about 0.15 clo), that was used by the participants during the test. The final value of the clothing resistance used for the calculation of the real-time PMV during the tests was equal to 0.96 clo.

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