Provision of thermal comfort via user-centric radiant cooling elements: An experimental investigation

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ABSTRACT

This contribution explores the performance of a user-centric radiant cooling approach. In comparison to conventional radiant cooling solutions, this approach *i)* positions radiant panels in close proximity to occupants, and *ii)* allows for panel surfaces temperatures below dew point and thus for potential surface condensation, which is dealt with via integrated water collection devices. The user-centric radiant panels were tested in a laboratory setting. Prototypical panels were installed in two mock-up office rooms. Twenty-eight participants evaluated thermal comfort (including radiant asymmetry and local thermal discomfort) for eight scenarios, including multiple panel surface temperatures as well as different ambient air temperatures. The results provide insights into the potential and limits of the proposed approach. Specifically, the findings pertain to panel surface temperatures, which are necessary to provide thermally comfortable conditions, as well as to surface condensation and radiant asymmetry.

INTRODUCTION

The cooling demand of buildings has rapidly increased within the last decades. Contributing factors to this development are rising temperatures caused by climate change and urban heat islands (IEA 2018). Given the negative consequences of these phenomena, there is a need for innovative cooling solutions that are energy efficient and provide building users with thermal comfort. Radiant cooling systems have been suggested to address both of these requirements (Rhee and Kim 2015). Nonetheless, the application of conventional radiant cooling systems must take a number of challenges into consideration, including water vapour condensation risk and interface with ventilation systems (Rhee and Kim 2015, Rhee et al. 2017, Tang et al. 2016). This makes the implementation of conventional radiant cooling systems difficult, especially in hot and humid climatic conditions involving high moisture concentrations in ambient air.

In this context, the present contribution focuses on a previously presented concept, namely the user-centric radiant cooling panels (Mahdavi and Teufl 2020). This cooling strategy addresses the aforementioned challenges by: *i)* placing vertical radiant cooling elements in proximity to occupants (we refer to this approach as “user-centric”), and *ii)* allowing condensation to occur, which is dealt with via integrated drainage elements. Due to these adaptations, the system is compatible with natural ventilation even in locations with a high-moisture ambient air. Specifically, lower panel surface temperatures can be maintained, increasing thus the cooling capacity. However, despite these advantages, radiant cooling systems are sometimes criticised to cause local thermal discomfort and radiant asymmetry.

In this context, this contribution addresses not only the overall thermal comfort implications of the user-centric panels but also their effects on local thermal discomfort. To this end, we report on a preliminary empirical investigation of the performance of prototypical user-centric radiant cooling elements (Teufl et al. 2021a). The cooling panels were installed in two mock-up office units of a laboratory. The participants of the experiment were seated at a workstation close to one of the radiant cooling panels and were requested to evaluate thermal comfort. Thereby, different settings were tested with regard to panel surface temperature (ranging from 30 °C down to 10 °C) and ambient air temperature (28 and 30 °C). The ambient relative humidity was kept at a constant level of 45%.

Ambient conditions, including radiant asymmetry, were recorded. Participants' subjective comfort evaluations were compared with respective measurements and calculations.

A CASE STUDY

Approach

The performance of the aforementioned user-centric radiant cooling elements was tested in a laboratory setting. The aim of this empirical study was to analyse the cooling panels' potential for thermal comfort provision. The main focus of this paper is to explore the panels' effects on general and local thermal comfort.

The experiments were conducted in the autumn of 2020. Prototypical radiant cooling panels (made of prefabricated elements) were installed in two mock-up office rooms of our Department's laboratory in Vienna, Austria. The volume of each office room is 28.7 m^3. Chilled water that can be circulated through the panels was provided by a water chiller. A container was integrated underneath the vertical cooling panels to collect potential surface condensation. Furthermore, heating devices and humidifiers were installed in each office unit to maintain target ambient air temperatures and humidity levels. The floor plan of the two identically equipped office units is shown in Figure 1. Figure 2 illustrates the dimensions of the radiant cooling panel. The experimental setup in one of the rooms is depicted in Figure 3. Twenty-eight participants were involved in this study. Note that, due to the small number of participants, the findings are not suggested to represent statistically significant results. Rather, the objective was to gain a preliminary impression of the user-centric cooling panels' performance.

Two-thirds of the participants were female and one third male (mean age: 31 ± 12). Since this study focuses on summer conditions, all participants were dressed in summer clothing (clo-value: 0.56 ± 0.05). In the course of this study, each person participated in two 135-minute sessions (see Figure 4). In between these sessions, participants made a break outside of the office unit. During the first session, the ambient air temperature in the office room was kept at 28 ± 0.3 °C and the relative humidity at 45 ± 2 %. While the relative humidity level was not changed for the second session, the ambient air temperature was increased to 30 ± 0.3 °C. Each of the two sessions consists of four parts. In each part, different panel surface temperatures were maintained. The first part of each session represents a base case. In these cases, the target surface temperature of the radiant element was equal to the ambient air temperature (28°C in Session 1 and 30°C in Session 2). Afterwards the panel surface temperature was stepwise reduced. The target temperatures were 19, 14, and 10 °C. Given specific panel surface and enclosure temperature values, the cooling power of the radiant panel can be estimated based on radiation exchange computation. At an ambient air temperature of 30°C and a panel surface temperature of 10°C the cooling power (per square meter panel area) was estimated to be roughly 100 W.

In the course of this study, every person participated in eight different scenarios. Table 1 shows an overview of these scenarios. A detailed timeline of the experiments is shown in Figure 4.During the experiments, participants were seated in one of the office rooms next to a cooling panel (see Figure 2 and 3). Participants conducted different tasks on a computer. At the start of the experiment, they were asked to a fill a questionnaire to provide general background information (Q0 in Figure 4). At the end of each scenario, they completed further questionnaires in which they evaluated the thermal conditions within the office units (Q1 to Q8 in Figure 4). These questionnaires included the thermal sensation vote (TSV, 7-point scale), thermal comfort vote (TCV, 6-point scale), and thermal acceptability vote (TAV, 6-point scale). Moreover, participants evaluated the air quality, air movement, and if they perceived any local thermal discomfort. The latter aspect was evaluated for multiple body parts, including the head, upper body, right and left arm, as well as right and left foot. Table 2 includes a selection of questions in more detail. The assigned numeric values for each answer are presented as well.

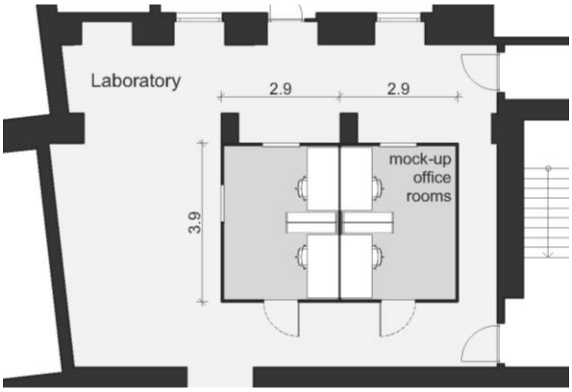

Figure 1. Floor plan of the mock-up office rooms in the laboratory space (dimensions in meter)

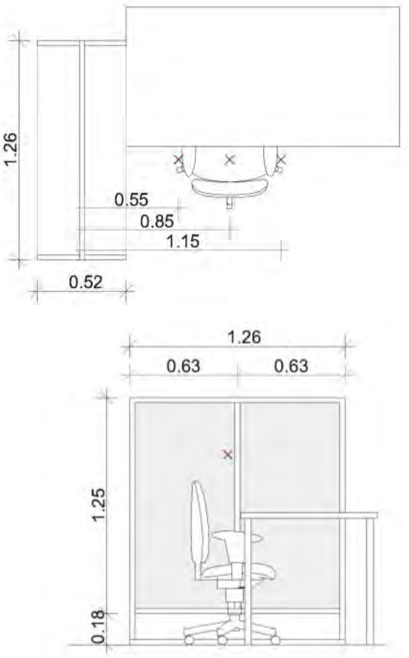

Figure 2. Floor plan (up) and elevation view (down) of the experimental setup including positions (marked as x) of the radiant temperature asymmetry measurements (ions in meter)

Figure 3. Experimental setup in Room A

Table 1. Evaluated scenarios of the case study

Scenarios	S1	S2	S3	S4	S5	S6	S7	S8
Mean panel surface temperature [°C]	28	19	14	10	30	19	14	10
Dew point [°C]	14.9				16.8			
Air temperature [°C]	28				30			
Relative humidity [%]	45							

Table 2. Selection of main questions and corresponding evaluation scales

<table>
<tr><th colspan="7">How would you evaluate thermal conditions right now in this room?</th></tr>
<tr><td>hot</td><td>warm</td><td>slightly warm</td><td>neutral</td><td>slightly cool</td><td>cool</td><td>cold</td></tr>
<tr><td>3</td><td>2</td><td>1</td><td>0</td><td>-1</td><td>-2</td><td>-3</td></tr>
<tr><th colspan="7">Do you find the thermal environment at this moment acceptable?</th></tr>
<tr><td>completely unacceptable</td><td>unacceptable</td><td>just unacceptable</td><td>just acceptable</td><td>acceptable</td><td colspan="2">completely acceptable</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td colspan="2">6</td></tr>
<tr><th colspan="7">Are you currently thermally comfortable?</th></tr>
<tr><td>very uncomfortable</td><td>uncomfortable</td><td>slightly uncomfortable</td><td>slightly comfortable</td><td>comfortable</td><td colspan="2">very comfortable</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td colspan="2">6</td></tr>
<tr><th colspan="7">Do you feel local thermal discomfort? (This question was asked for head, upper body, right arm, left arm, right foot and left foot.)</th></tr>
<tr><td colspan="2">no</td><td colspan="2">slight</td><td colspan="2">moderate</td><td>strong</td></tr>
<tr><td colspan="2">0</td><td colspan="2">1</td><td colspan="2">2</td><td>3</td></tr>
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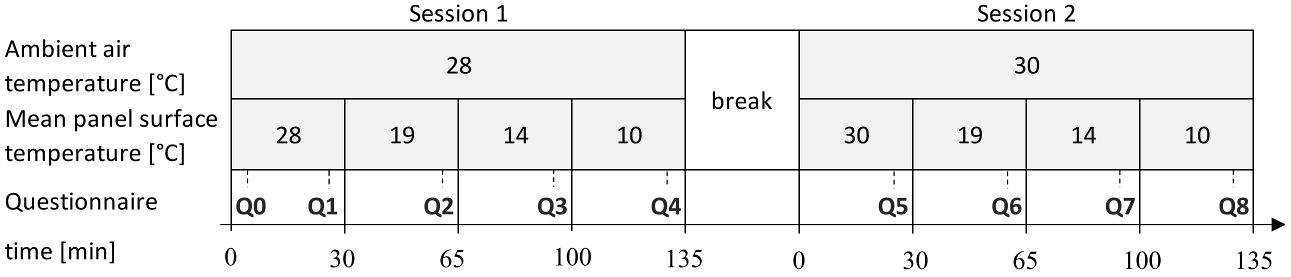

Figure 4. Timeline of the experiment

During the experiments, parameters such as the ambient air temperature, relative humidity, and air flow speed were measured at the workstation in one-minute intervals. Further indoor environmental parameters (the CO_2 concentration, ambient air temperature, and relative humidity) were measured in two other locations in the office unit. Moreover, the panels' surface temperature was measured at six positions. The term "mean panel surface temperature" as used in this paper denotes the mean value of the temperature at these six positions.

The radiant temperature asymmetry was assessed in a separate experimental investigation in accordance with ISO 7726 (2001). This was done for all scenarios in which the radiant cooling panel was activated (see Table 1). The radiant temperature asymmetry was obtained for different measurement positions, including at three different distances from the radiant cooling panel, namely 55 cm, 85 cm (position of the occupant), and 115 cm (see Figure 2). All measurements were conducted at a height of 110 cm, which corresponds to the assumed default position of a seated persons' head (ISO 7726:2001).

Results

Figures 5 to 14 show the outcome of the experimental investigation. More specifically, they present the distributions of participants' subjective evaluation of thermal sensation (Figures 5 and 6), thermal comfort (Figures 7 and 8), and thermal acceptability (Figures 9 and 10). To facilitate a more convenient comparison of these distributions, they are shown in these figures in terms of respective fitted curves. Thereby, the outcome is shown for all eight scenarios, including the ambient air temperatures 28°C and 30°C as well as the four different panel surface temperatures. The numeric values of the x-axis refer to scale steps entailed in Table 2.

Table 3 shows the measured radiant temperature asymmetry values for multiple panel surface temperatures (19, 14, and 10 °C) and ambient air temperatures of 28 and 30°C. These results were found to match well with calculated radiant temperature asymmetry values based on view factors and pertinent surface temperatures. Specifically, the difference between measurements and calculations was found to be 0.3 ±0.3 K.

Figure 11 to 14 show participants' perceived local thermal discomfort (as relevant to participants' arms). The evaluation regarding the head, upper body, and feet are summarized in Table 4.

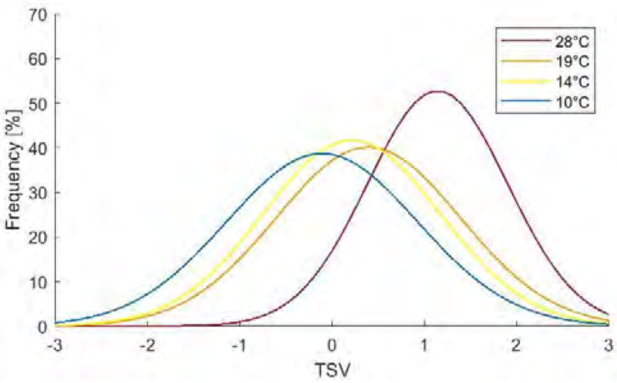

Figure 5. Frequency of participants' thermal sensation votes at an ambient air temperature of 28°C

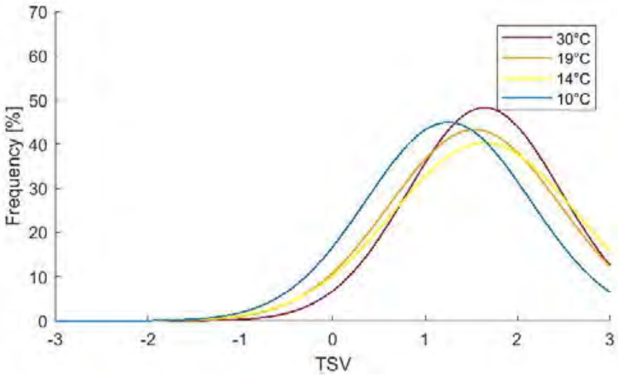

Figure 6. Frequency of participants' thermal sensation votes at an ambient air temperature of 30°C

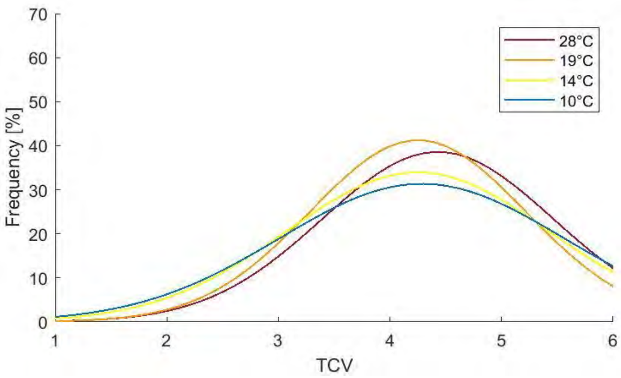

Figure 7. Frequency of participants' thermal comfort votes at an ambient air temperature of 28°C

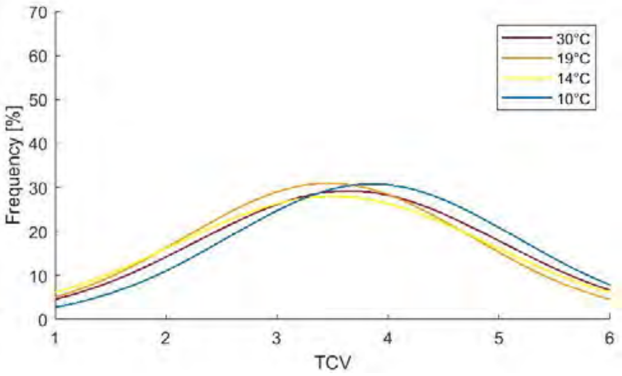

Figure 8. Frequency of participants' thermal comfort votes at an ambient air temperature of 30°C

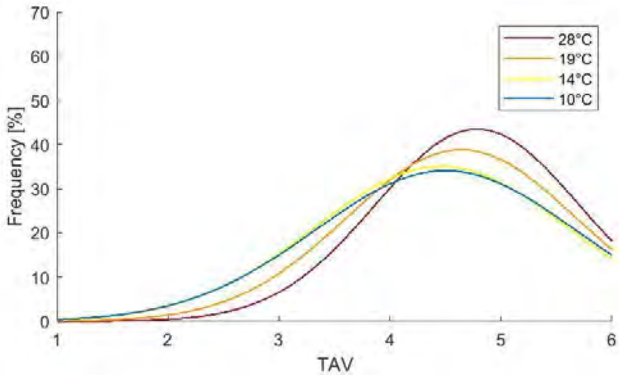

Figure 9. Frequency of participants' thermal acceptability votes at an ambient air temperature of 28°C

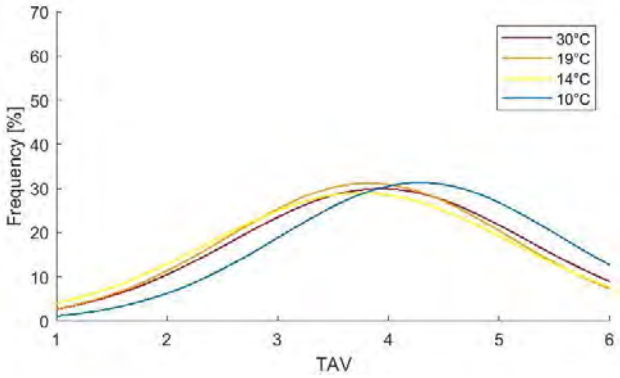

Figure 10. Frequency of participants' thermal acceptability votes at an ambient air temperature of 30°C

Table 3. Radiant temperature asymmetry Δt_{pr} (in kelvin) for multiple scenarios

Distance to panel [cm]	Scenarios					
	S2	**S3**	**S4**	**S6**	**S7**	**S8**
55	3.3	4.9	7.0	3.5	5.0	7.1
85	1.5	2.6	3.9	2.2	2.9	4.1
115	1.2	1.7	2.4	1.3	1.8	2.7

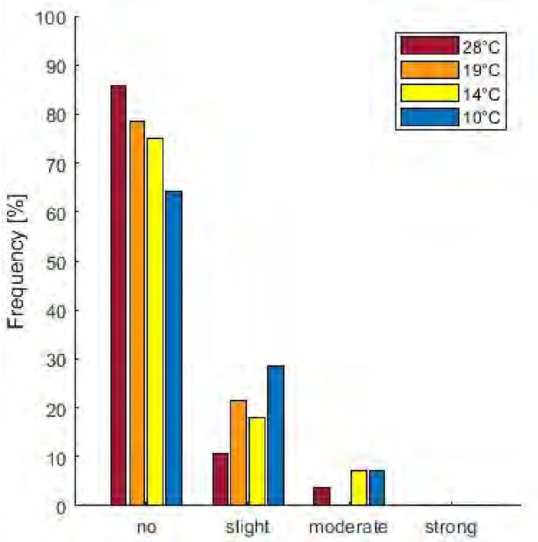

Figure 11. Participants' evaluation of local thermal discomfort (arm close to the panel) at an ambient air temperature of 28°C

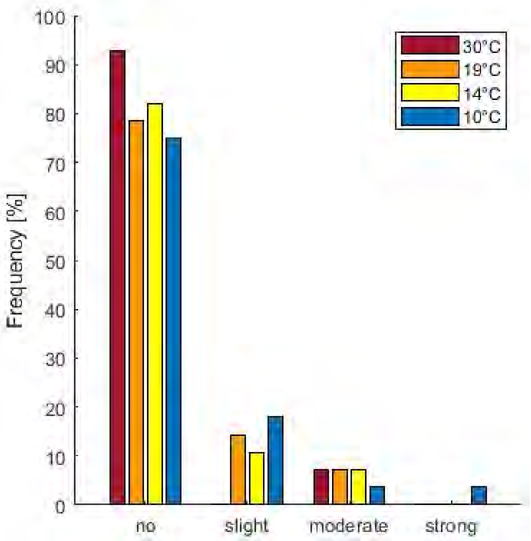

Figure 12. Participants' evaluation of local thermal discomfort (arm close to the panel) at an ambient air temperature of 30°C

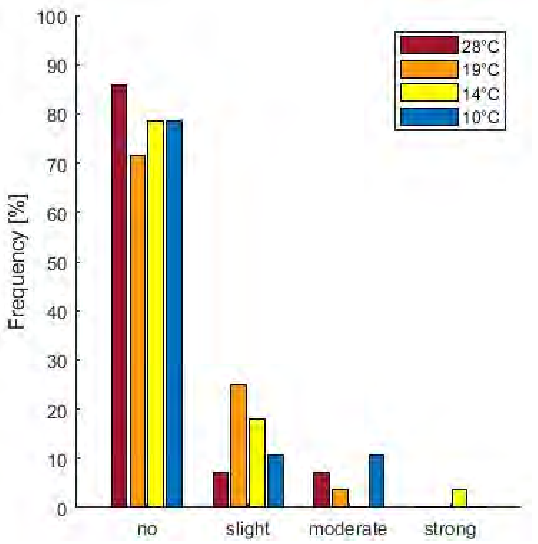

Figure 13. Participants' evaluation of local thermal discomfort (arm away from the panel) at an ambient air temperature of 28°C

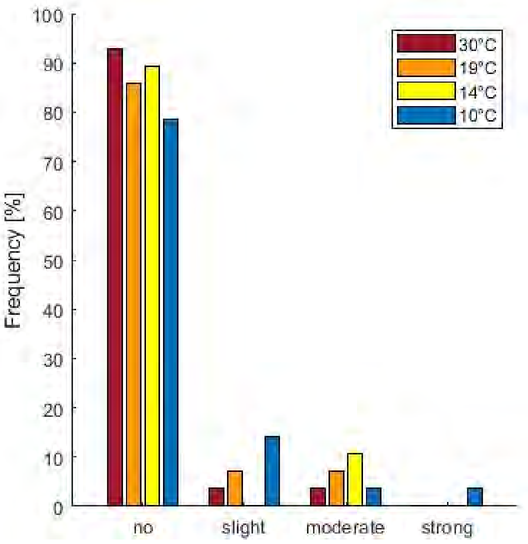

Figure 14. Participants' evaluation of local thermal discomfort (arm away from the panel) at an ambient air temperature of 30°C

Table 4. Frequency of participants' local thermal discomfort votes (head, upper body, and feet) in percent for the four different panel surface temperatures at an ambient air temperature of 28 and 30°C

	Panel surface temperature															
	28/30°C (S1 and S5)				19°C (S2 and S6)				14°C (S3 and S7)				10°C (S4 and S8)			
Vote	no	slight	moderate	strong	no	slight	moderate	strong	no	slight	moderate	strong	no	slight	moderate	strong
Head	77	13	9	2	73	13	11	4	71	11	13	5	75	14	5	5
Upper Body	82	11	7	0	75	16	7	2	75	16	7	2	82	14	2	2
Foot (close to panel)	89	9	2	0	88	9	4	0	77	16	7	0	80	16	4	0
Foot (away from panel)	89	7	4	0	88	9	4	0	82	14	4	0	80	14	5	0

Discussion

The aim of this study was to gain a first impression of the user-centric cooling panels' performance with regard to thermal comfort. As mentioned before, only a small number of people participated in this experimental investigation. Nonetheless, this preliminary study can reveal general tendencies and present a first impression of the cooling panels' performance under specific conditions.

The results of the study show that the user-centric radiant cooling panels can influence occupants' thermal sensation. This is clearly noticeable at an ambient air temperature of 28°C (see Figure 5, scenarios S1 to S4). In the base case (scenario S1), in which the panel's surface temperature was equal to the ambient air temperature, the mean thermal sensation vote of all participants is +1.1. By reducing the panel surface temperature, the mean thermal sensation of participants shifted closer to 0, which corresponds to a thermal sensation of “neutral” (+0.4, +0.2, and -0.1 at a panel surface temperature of 19, 14, and 10°C, respectively). At an ambient air temperature of 30°C (see Figure 6, scenarios S5 to S8) this effect is also visible but less pronounced. Generally speaking, a notable thermal comfort improvement can be observed mainly at a less extreme ambient air temperature (28°C, scenarios S1-S4), and a rather low panel surface temperature. At higher temperatures, the radiant panels could be supported by the incorporation of additional convective cooling solutions such as fans.

When it comes to participants' evaluation of thermal comfort (see Figures 7 and 8) and thermal acceptability (see Figures 9 and 10), a lower panel surface temperature did not reveal a clear improvement. At an ambient air temperature of 30°C, thermal comfort and thermal acceptability were rated slightly better once the panel surface temperature was reduce to 10°C (see Figure 8 and 10, scenario S8). However, at an ambient air temperature of 28°C, a lower panel surface temperature did not reveal an improvement. A reason for this outcome might be perceived local thermal discomfort. In this context, it is noticeable that at an ambient air temperature of 28°C slightly more participants perceived thermal discomfort at their arms, in comparison to the scenarios with an air temperature of 30°C (see Figures 11 to 14).

Participant's evaluation of local thermal discomfort shows that the majority did not perceive local thermal discomfort during the tested scenarios. Specifically interesting for assessing the influence of the user-centric radiant panels on local thermal discomfort are participants' evaluations of the arm and foot close to the panel in comparison to the ones further away. In case of the arms, the results show that a lower panel surface temperature results in more participants perceiving local thermal discomfort. Furthermore, as expected, a comparison of the evaluation of the arm close to the panel to the one further away showed that more participants perceived local thermal discomfort at the arm in close proximity to the cooling element. Nonetheless, as mentioned before, the majority of participants did not perceive local thermal discomfort, even at the arm close to the radiant panel.

Concerning local discomfort regarding feet, a rather small difference can be discerned between the evaluations of the foot next to the panel and the one further away. A reason for this outcome can be the fact that nearly all participants were wearing trousers and closed shoes, covering their legs and feet.

The assessment of the radiant temperature asymmetry revealed rather low values for all scenarios. Even in case of scenario S8 (30°C air temperature and 10°C mean panel surface temperature) the radiant temperature asymmetry is 4.1 K at the occupants' seating position (85 cm from the panel). This results in a PD (percentage dissatisfied) of less than 1% (ISO 7730:2006).

The present treatment did not include air flow velocities in close proximity to the radiant cooling panel and their potential influence on occupants' thermal comfort. However, this issue was addressed in a separate study (Teufl et al. 2021b). Thereby, no risk of draft discomfort at the occupants seating position was detected.

CONCLUSION

This paper focused on an alternative radiant cooling approach, which allows lower surfaces temperatures than conventional solutions by *i)* using vertical panels close to a user and *ii)* incorporating drainage systems for potential surface condensation (Mahdavi and Teufl 2020).

Prototypical radiant cooling panels were installed in a laboratory. A small number of people participated in an experimental investigation and evaluated thermal comfort (including radiant asymmetry and local thermal discomfort) for eight different scenarios comprising different ambient air and panel surface temperatures.

The outcome of this study points both to the potential and – in certain situations – to the limitations of the proposed approach. A notable improvement of participants' thermal sensation due to the chilled user-centric panels was mainly visible at an ambient air temperature of 28°C (scenarios S1-S4). This effect was still present but less pronounced at an ambient air temperature of 30°C (scenarios S5-S8). This suggests that the proposed alternative radiant cooling approach may be less effective at extremely high ambient air temperatures. In such cases, additional convective cooling solutions involving for instance, ceiling or desktop fans can supplement radiant panels toward provision of sufficient cooling performance levels.

Concerning local thermal discomfort, the results suggest that a slightly larger number of participants perceived local thermal discomfort at the arm region in close proximity to the cooling element in comparison to the arm further away. Moreover, it is noticeable that lower panel surface temperatures resulted in more participants perceiving local discomfort. Nonetheless, it has to be mentioned that the majority of participants did not perceive local thermal discomfort at their arms and feet, even in situations with rather low panel surface temperatures. Moreover, the assessment of the radiant temperature asymmetry did not reveal any potentially negative aspect regarding the functionality of the proposed radiant cooling approach.

In the course of future studies, we intend to further investigate, in more detail, the performance and effectiveness of user-centric radiant cooling panels. This shall include the inclusion of a larger and more representative number of participants. Furthermore, the energy saving potential of the user-centric panels (as compared to other space cooling solutions) will be explored.

ACKNOWLEDGMENTS

In their studies of alternative space cooling approaches in general and radiant cooling solutions in particular, the authors have benefited from discussions in the context of the IEA EBC Annex 80.

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