Computational assessment of occupant-centric radiant cooling solutions

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Abstract
This paper entails the computational assessment of a number of occupant-centric radiant cooling elements. These radiant elements are positioned close to users and can accommodate potential surface condensation. As such, they can be operated with panel surface temperatures below the dew point. The computational assessment focuses on their effects on occupants’ thermal comfort. To this end, four different climatic regions are considered. The results point to both the potential of the proposed radiant cooling approach and the limitations, especially with regard to extremely hot and humid conditions.

Key innovations
- In comparison to conventional radiant cooling solutions, the alternative designs are positioned closer to occupants, which is suggested to enhance energy efficiency and personal control.
- By incorporating systems to accommodate surface condensation, lower panel surface temperatures are possible.
- The proposed radiant cooling panels are compatible with natural ventilation even in very humid climatic regions. Furthermore, they can be implemented in existing buildings even if they are not very air tight.

Practical implications
This contribution describes the implications of different design and operation features of occupant-centric radiant cooling panels for occupants' thermal comfort. Related simulations results are presented, together with a graphical option to derive the necessary panel size and surface temperature.

Introduction
Buildings’ increasing cooling energy use has been attributed to phenomena such as global warming and urban heat islands (IEA, 2018). This underlines the need for innovative cooling solutions. In this context, radiant cooling technologies have been promoted because they have the potential to improve the energy efficiency as well as occupants' thermal comfort (Rhee and Kim, 2015; Rhee et al., 2017). Nonetheless, some important aspects must be considered when designing and implementing radiant cooling systems (e.g., buildings’ climatic context, position of the radiant elements relative to occupants, water vapour condensation risk).

A previously proposed radiant cooling approach is intended to address these aspects (Mahdavi and Teufl, 2020). This approach is guided by three main concepts. The first concept (referred to here as “occupant-centric”) involves the positioning of radiant panels in close proximity to occupants. This has the potential to enhance both energy efficiency and personal control. The second concept concerns the surface temperature of the radiant element. In comparison to conventional radiant cooling solutions, the proposed approach allows for and accommodates surface condensation via condensed water collection elements. Thus, lower panel surface temperatures (below dewpoint) are possible. The third concept, which is not treated in the present contribution, involves the additional option of incorporating an appropriately selected vegetation layer into the designs (Mahdavi and Teufl, 2020). Such a layer could contribute to the appearance of the radiant panels. Moreover, placed below the vertical radiant panel, the container for the layer’s substrate can act as the collector of condensed water.

This contribution presents a computational examination of the aforementioned solution. Specifically, methods and tools are discussed that can support the derivation of the necessary panel sizes and surface temperatures to provide thermal comfort for building users. This is illustrated for several thermal conditions including, for example, various air temperatures, air flow speeds, and relative humidity values.

A further computational examination is conducted for a typical open-plan office setting. The aim of this study was to evaluate occupants’ thermal comfort under – virtually implemented – operation of the proposed radiant panel solutions. Thereby, multiple design variations are probed including panels positioned on one or two sides of a typical workstation. The study was conducted for four different climatic regions (from hot dry to hot humid).

Estimating the comfort implications of radiant panel configurations
A preliminary computational assessment explored the thermal comfort implications of radiant elements positioned in the close proximity of occupants. Thereby, the main objective was to device a simple procedure (including software and graphical support material) to support the configuration process of occupant-centric
cooling panels. To describe this procedure, consider possible steps (see Figures 1 to 3) toward estimating the thermal comfort implications of specific system parameters, such as the panel size and panel surface temperature. The procedure's functionality can be illustrated using a common performance indicator relevant to thermal comfort, namely the Predicted Mean Vote (PMV). This indicator is based on a seven-point thermal sensation scale (ASHRAE, 2017). It ranges from a value of -3 to +3, which refers to a subjective evaluation from "cold" to "hot". Typically, it is recommended that the PMV is kept within the range of -0.5 and +0.5. In the course of this study, the PMV was calculated based on the ASHRAE 55 standard (ASHRAE, 2017). More specifically, the PMV with elevated air speed method was used, if the air flow speed was equal or higher than 0.2 m.s\(^{-1}\). The PMV was calculated for several scenarios, including multiple air temperatures, air flow speeds, as well as a relative humidity of 30, 50, and 70%. In all cases the metabolic rate was set to 1.1 and a clothing value of 0.5 was used, which corresponds to typical summer clothing (ASHRAE, 2017). Furthermore, the mean radiant temperature (MRT) was estimated using Equation 1. Thereby, the simplifying assumption was made that, with the exception of the radiant panel, the temperature of all room's surfaces is equal to the air temperature.

\[
MRT = \frac{\theta_{\text{panel}}\Omega_{\text{panel}} + \theta_{\text{air}}(4\pi - \Omega_{\text{panel}}))}{4\pi}
\]

(1)

Here, \(\theta_{\text{panel}}\) and \(\Omega_{\text{panel}}\) denote the panel surface temperature and the view angle from the occupant's position to the radiant panel respectively.

Consider a query with regard to the necessary panel size and surface temperature in order for PMV to be kept below 0 ("neutral"), below +0.5 (recommended upper limit), or below +1 ("slightly warm"). Figures 1 to 3 illustrate how such a query can be addressed.

Using Figure 1, and given specific values for indoor air relative humidity (30%, 50%, 70%), and occupants’ clothing (0.5 clo) and activity levels (1.1 met), the maximum operative temperature and the minimum air flow speed can be obtained, which would yield a PMV below the aforementioned thresholds (0, +0.5, or +1).

Given a target value of operative temperature (obtained, for instance, via Figure 1) for a given ambient air temperature, Figures 2 and 3 show the required minimum panel surface temperature. These figures pertain to two configurations concerning panel size and its distance to the occupant. Figure 2 shows the outcome if the fraction of the solid angle from the occupant to the panel (\(\Omega_{\text{panel}}/4\pi\)), expressed in percentage, is 10%. Figure 3 shows the results if this fraction is 20%.

These graphs also include minimum panel surface temperatures to avoid surface condensation at indoor air relative humidity levels of 30, 50, and 70%.
A computational case study

Method

To obtain a general impression with regard to the radiant panels' practical effectiveness under different climatic conditions, we considered a typical open-plan (landscape) office setting (Teuff and Mahdavi, 2020). The selected office space has a floor area of 100 m² and incorporates four windows (one facing north, south, west, and east). Four distinct climatic conditions were considered, represented by four locations, namely Vienna (Austria), Valencia (Spain), Albuquerque (New Mexico, USA), and Singapore. The climatic conditions in these locations range from moderate to hot and humid (see Table 1). Moreover, Figures 4 and 5 present a cumulative distribution of the exterior temperature and relative humidity for each of these locations. Since this study is only focusing on three of the warmest months (June-August), the figures solely present the data for this time period.

Indoor air temperature in a typical open plan office was obtained using a numeric simulation tool (EnergyPlus, 2017) and standard weather files for the four locations (EnergyPlus, 2020). Input assumptions for the simulation model are summarized in Table 2. As mentioned before, the occupant-centric radiant cooling solution is compatible with natural ventilation. As a result, we assumed that the office spaces are also naturally ventilated. To facilitate the comparability of the results, the same assumed ventilation rate of 2 air changes per hour was used in all simulations.

The study explored different variations of the radiant cooling elements. This includes panels positioned on one or two sides of typical workstations. For comparison purposes, cases without cooling panels (base-case scenarios) were explored as well. Figure 6 shows the workstation arrangement for one or two radiant panels and the corresponding dimensions.

In this case too, PMV was computed as the thermal comfort indicator in accordance with ASHREA 55 (ASHRAE, 2017). The metabolic rate and clothing value were set to 1.1 and 0.5, respectively. The mean radiant temperature was estimated using Equation 1. Thereby, the surface temperature of the radiant panels were assumed to be 12°C during all those intervals, whose computed base-case PMV (no radiant cooling) is above 0.5, and otherwise equal to air temperature. Concerning the air flow speed, a fixed value of 0.2 m.s⁻¹ was selected for the entire evaluation period. The effects of an increased air flow speed due to an additional fan were analysed as well. In these cases, the PMV was calculated using an air flow speed of 0.7 or 1 m.s⁻¹.

Table 1. Thermal conditions in Vienna, Valencia, Albuquerque, and Singapore.

<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature</th>
<th>Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vienna</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Valencia</td>
<td>Moderate</td>
<td>Rather high</td>
</tr>
<tr>
<td>Albuquerque</td>
<td>Rather high</td>
<td>Low</td>
</tr>
<tr>
<td>Singapore</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Figure 4: Cumulative distribution of the exterior temperature (June-August) for the selected locations.

Figure 5: Cumulative distribution of the exterior relative humidity (June-August) for the selected locations.

Figure 6: Arrangement for one or two (illustrated as a dashed line in the plan) occupant-centric radiant panels (left: elevation; right: plan); dimensions in cm.

Table 2. Input parameters that were specified within the numeric simulation tool.

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Assigned value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor area</td>
<td>100 m²</td>
</tr>
<tr>
<td>Window area</td>
<td>5 m² per window</td>
</tr>
<tr>
<td>Window to wall ratio</td>
<td>15 %</td>
</tr>
<tr>
<td>Room height</td>
<td>3.5 m</td>
</tr>
<tr>
<td>U-value (wall)</td>
<td>0.116 W.m⁻².K⁻¹</td>
</tr>
<tr>
<td>U-value (windows)</td>
<td>1.196 W.m⁻².K⁻¹</td>
</tr>
<tr>
<td>SHGC (windows)</td>
<td>0.31</td>
</tr>
<tr>
<td>Internal loads</td>
<td>Lights: 6.9 W.m⁻²; Electric equip.: 8.1 W.m⁻²; People: 9.2 W.m⁻²</td>
</tr>
<tr>
<td>Ventilation rate</td>
<td>2 Air Changes per Hour</td>
</tr>
<tr>
<td>Schedules</td>
<td>Schedules Office Occupancy and Lighting (ASHRAE, 1989)</td>
</tr>
</tbody>
</table>
Results

Figures 7 and 8 show the indoor temperatures and relative humidity values, which were obtained by numeric simulation. The data is presented for all locations via cumulative distributions.

The outcome of the PMV calculations is presented in Figures 9 to 16. More specifically, the percentage of time during the assumed office working hours (8:00 am - 6:00 pm) is shown in which the PMV exceeds the recommended limit of +0.5 (see Figures 9, and 11 to 13). Figures 10 and 14 to 16 illustrate the percentage of time in which a PMV of +1 (“slightly warm”) is exceeded. The results suggest that by positioning radiant panels in close proximity to occupants, the percentage of time with higher thermal discomfort probability (PMV > 0.5), can be reduced. In case of Vienna, even without an elevated air flow speed by an additional fan, the percentage of time in which the PMV exceeds +0.5 can be reduced from 23 to 5 percent if two operating radiant panels are positioned close to the user. Furthermore, by using occupant-centric radiant panels, the PMV almost never exceeds a value of +1.0 (see Figure 10).

Likewise, the results suggest that also in Valencia, the occupant-centric radiant panels can improve user thermal comfort. By incorporating an additional fan and hence increasing the air flow speed, a further significant reduction can be achieved. Assuming two operating radiant panels and elevated air speed, the PMV rarely exceeds +1.0 (“slightly warm”).

Figure 12 and 15 show the outcome for Albuquerque, New Mexico. The results of the base-case suggest that the PMV is 88 percent of the time above the recommended limit of +0.5. By using radiant panels, this value can be reduced to 60 or 32 percent depending on whether an additional fan is incorporated or not.

In case of Singapore, only a slight thermal comfort improvement is visible. Due to the extremely hot and humid climate, without a radiant panel the PMV exceeds +0.5 the entire time. With two radiant panels and elevated air flow speed this can be reduced to 78 percent.
Figure 1: Percentage of time in which the PMV exceeds +0.5 (within the assumed working hours) in Valencia.

Figure 2: Percentage of time in which the PMV exceeds +0.5 (within assumed working hours) in Albuquerque.

Figure 3: Percentage of time in which the PMV exceeds +0.5 (within the assumed working hours) in Singapore.

Figure 4: Percentage of time in which the PMV exceeds +1.0 (within the assumed working hours) in Valencia.

Figure 5: Percentage of time in which the PMV exceeds +1.0 (within assumed working hours) in Albuquerque.

Figure 6: Percentage of time in which the PMV exceeds +1.0 (within the assumed working hours) in Singapore.
Discussion

We computationally explored the effects of occupant-centric radiant cooling panels on users' thermal comfort. We presented a simple procedure that can support the derivation of the size and surface temperature of radiant panels was presented (see Figures 1 to 3). A more in-depth simulation study considered radiant cooling panels for an office setting in four different climatic regions. The results suggest that by using radiant panels in close proximity to occupants, the percentage of time with higher thermal discomfort probability can be noticeably reduced. Nonetheless, at very hot and humid climatic conditions, such as in Singapore, this reduction effect is less pronounced. The incorporation of an additional fan can further assist to reduce thermal discomfort.

In this context, the results of the study suggest that the increased air flow speed of an additional fan can have a significant influence on the results (Figures 9 to 16). However, it should be kept in mind that an overly elevated air flow speed can also result in discomfort caused by the perception of draft. In comparison, radiant cooling panels can provide draft free cooling. Note that the provision of cooling power in these scenarios involved, in multiple cases, panel surface temperatures below dew point. This can be dealt with, however, given that the proposed concept incorporates elements to collect condensed water.

Moreover, it has to be mentioned that PMV might be overestimated in naturally ventilated spaces. Nonetheless, since PMV is a frequently used indicator for thermal comfort, it was used in our study to characterize the system's performance level in relative terms. Furthermore, even if the calculated PMV values would be slightly overestimated, they would be still "on the safe side", i.e., the system's performance would not be unduly overestimated.

Ongoing research

We are currently exploring the performance of the proposed radiant panels in a laboratory setting. Thereby, participants evaluate thermal conditions via questionnaires recording thermal sensation votes (TSV), which also refers to a seven-point thermal sensation scale ranging from -3 ("cold"), to +3 ("hot"). To this end, prototypical panels have been installed in two mock-up office rooms. Multiple operation scenarios (different ambient air temperature and panel surface temperatures) are being considered. Given the small number of human participants so far (twenty-eight), the results cannot be considered representative or generalizable (Teufl et al., 2021). To communicate an impression of one of the initial outcomes of this study, Figure 17 shows the comparison of participants' subjective TSVs with the calculated PMVs for the same ambient and operational conditions. This comparison suggests, as it can be seen from Figure 17, that PMV and TSV values agree quite well at the very high ambient air temperature of 30°C. At an air temperature of 28°C, the two values begin to diverge, once the surface temperature of the radiant panel is reduced (see Figure 17). In other words, at this somewhat lower temperature, participants evaluated thermal comfort more favourably than it could be expected from a PMV-based assessment. This tendency, in case confirmed through further data, would suggest that one would be "on the safe side" when using the procedure illustrated in Figures 1 to 3 to derive the size and surface temperature of the radiant panels.

Another important aspect not addressed in the present contribution is the panels' effect on radiant asymmetry. We are currently exploring this issue in a laboratory setting. Thereby, the radiant asymmetry is being empirically obtained for various combinations of panel surface temperature and room air temperature. The results obtained thus far, do not point to a local thermal discomfort risk.

Finally we need to mention a limitation of the study concerning the window to wall ratio assumption. This ratio (15%) is on the lower range. Specifically, typical office buildings display higher ratios. In those cases, however, buildings typically provide shading devices, thus practically reducing the effective glazing area in view of solar heat gains. To manage the level of complexity in parametric simulations conducted in the present study, the shading operation and its dynamics was not modelled in detail. Hence, the selected lower window to wall ratio was meant to consider – in a simplified manner – the reduction of the effective glazing area due to shading. As with other influencing factors (air exchange rates), we intend to address the implications of a more detailed (dynamic) modelling approach in follow-up studies.

![Figure 17: The relationship between TSV and the calculated mean values of PMV (Teufl et al., 2021).](https://doi.org/10.26868/25222708.2021.30182)
Conclusion
This contribution explored the performance of an alternative radiant cooling approach. In comparison to conventional radiant cooling elements, this approach involves the close proximity of the radiant panels to occupants. Furthermore, the vertical radiant panels are equipped with containers to collect potential surface condensation. As a result, the surface temperature of the radiant elements can be set below the dew point temperature.

Two simulation-based studies were presented, exploring the thermal comfort implications of the aforementioned radiant panels. The first examination discusses a procedure to define necessary panel sizes and surface temperatures to improve thermal comfort conditions. The second examination focuses on the panels’ practical effectiveness in different climatic regions (Vienna, Valencia, Albuquerque, and Singapore). This assessment was conducted for a typical open-plan office setting. The results of the study suggest that the implementation of occupant-centric radiant elements has the clear potential to reduce the thermal discomfort probability. Nonetheless, especially in extremely hot and humid conditions, the results also point to some limitations of the proposed approach.

We also alluded to an ongoing laboratory-based study of a prototypically realized office space with the mentioned radiant panel designs. Additional data to be collected in the course of this study (with more participants and a wider range of operational scenarios) is expected to further document the cooling effectiveness of occupant-centric radiant panels. Moreover, such data could also constitute a more solid empirical basis for the validation and calibration of the computational system design approaches.

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References