Laboratory tests of a prototypical user-centric radiant cooling solution

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Abstract. Radiant cooling systems are being increasingly promoted because of their energy efficient operation as well as their potential to improve occupants' thermal comfort due to a draft-free cooling process. This paper focuses on a specific radiant cooling approach, which was introduced in previous contributions. This approach involves the positioning of relatively small-sized vertical radiant panels in the close proximity to occupants. Furthermore, the panels incorporate drainage systems or collection elements to accommodate, if needed, water vapour condensation. Consequently, the surface temperature of the radiant panels does not need to stay above the dew point temperature. We present the outcome of a preliminary experimental investigation of such a personal radiant cooling system. In this context, prototypical radiant panels were installed in a laboratory and multiple experiments were conducted. The uniformity level of the panels' surface temperature distribution was documented. Moreover, near-panel air flow velocities were measured at several positions. Likewise, the formation of condensed water on panels was observed for different panel surface temperatures, room temperatures, and room humidity levels. The results of the preliminary laboratory investigation do not point to any risk of draft or turbulence discomfort.

1. Introduction
Radiant cooling systems have been suggested to have a number of advantages. They can reduce the need for excessive air flow rates thus reducing the size of ventilation systems and the respective energy use requirement [1]. Moreover, they can provide a draft-free cooling mode, which is considered favorable in view of human thermal comfort [2]. Nonetheless, when implementing these systems, a number of limitations need to be considered. One challenge pertains to the risk of water vapor condensation on the panels' surface. This has led to the conclusion that the surface temperature of conventional radiant cooling panels must stay above the dew point temperature, which can be especially challenging in humid climates with high moisture content in the air [2, 3]. In these climatic regions, radiant cooling technologies typically require the dehumidification of the incoming air. However, incorporating an additional ventilation system can be quite expensive. Furthermore, the buildings must be rather air tight to avoid infiltration. Since, this is often not the case when it comes to existing buildings, it might be difficult to install radiant cooling systems in these situations [3].

In this context, this contribution further explores the operation of a previously introduced "user-centric" radiant cooling approach [3, 4]. Thereby, in contrast to typical large-area (e.g., ceiling) panels, relatively small-sized vertical radiant panels are installed in the close proximity to occupants. Moreover, in comparison to conventional radiant cooling systems, this solution can facilitate lower panel surface temperatures, which, together with the shorter distance to the occupants, are intended to compensate for
the potential drop in cooling power due to the smaller size of the panels. The panel design includes resilient surfaces and integrated elements for condensed water collection, should the lower panel surface temperatures lead to water vapor condensation. Various designs for the condensed water collection elements have been conceived, including specific containers, drainage components, and even customized flowerboxes. In the latter case, the substrate layer can accommodate condensed water, while the plants can provide additional advantages such as improving the appearance of the panels [3]. Due to these precautions, the proposed solution can also be implemented in naturally ventilated buildings even in humid climatic conditions.

We have previously conducted a number of laboratory-based experiments to test the feasibility and overall thermal performance of prototypical implementation of the aforementioned cooling approach [5]. These experiments included also preliminary assessments of the perceived effectiveness of the occupant-centric panels by a small number of participants [5]. To conduct these preliminary investigations, prototypical radiant cooling panels were built and positioned in two laboratory rooms.

In this paper, we report on the results of a recent empirical examination of the air flow and temperature fields close to the radiant panels. One specific motivation behind these tests pertains to the assessment of the potential discomfort risk that may arise, if the velocity convective flows resulting from the temperature gradient between the panel's surface temperature and the ambient air could reach perceptible and uncomfortable levels. To conduct the measurements, specific target values for the panel surface temperature as well as default values of room air temperature and humidity were maintained. Moreover, the formation of condensed water on panels was observed.

2. Investigation of near-field air speed and temperature

2.1. Method

In the course of previous studies, two prototypical radiant cooling panels were built and installed in two rooms of the Building Science Laboratory at TU Wien in Vienna, Austria. A floor plan and picture of the laboratory space is shown in Figure 1. Condensed water collection trays were positioned below the radiant cooling panel. Furthermore, humidifiers and heaters were positioned in each laboratory room to keep the ambient air temperature and relative humidity at the desired values. A water chiller provided cold water, which was circulated through the personal radiant cooling panels.

Multiple experiments were conducted. Table 1 gives an overview of the used measurement devices. First, the surface temperature distribution of a panel was documented. In this context, we measured the surface temperature in several positions to explore the uniformity level of the radiant cooling panel's surface temperature. The measurement positions are shown in Figure 2. The target panel surface temperature, ambient air temperature, and relative humidity for these experiments were 10°C, 30°C, and 40% respectively. As monitored via the six surface temperature sensors (see illustration in Figure 2), these target values could be indeed maintained within reasonable ranges during the course of measurements. Specifically, the respective standard deviations of these target values were derived for each of the six surface temperature probes over the entire measurement period and found to be ±0.2 K. Likewise, the standard deviations of the measured ambient air temperature and relative humidity amounted to ±0.5 K and ±3% respectively.

The reference room air temperature was measured at the target position of a seated person (at a height of 110 cm above the floor and 85 cm from the panel). Air flow measurements were conducted at different heights (ranging from 10 to 110 cm) and different distances from the panel (1, 1.5, 2, 3, 4, 5, 10, 15, 20, 30, 40, and 50 cm). The corresponding sensor positions are shown in Figure 2 and 3. Note that the mentioned panel surface temperature of 10°C represents a target mean value over the entire panel area.

In a separate set of experiments, the formation of condensed water on panels was observed for multiple scenarios encompassing different panel surface temperatures (30, 28, 19, 14, and 10 °C) and ambient air temperatures (30 and 28°C). The scenarios for this set of experiments are presented in more detail in Table 2.
Figure 1. Schematic floor plan of the two mock-up office units (Rooms A and B) within the general laboratory space (left) and picture of the experimental setup (right), showing the radiant panel and the anemometer arrangement (vertical bar), as well as the precautionary container for the condensed water.

Table 1. Overview of the used measurement devices.

| Device                                      | Measured variable                                      | Range                  | Accuracy                                                                 |
|---------------------------------------------|---------------------------------------------------------|------------------------|--------------------------------------------------------------------------|
| Thermal comfort / indoor climate measurement station | Indoor air temperature and relative humidity (Sensirion SHT 75) | -40 .. 123.8 °C        | typ. ±0.3 K at 10 .. 40 °C                                               |
|                                             | Air velocity - omnidirectional (Swema 03: response time < 0.2 s) | 0.05 .. 3 m.s⁻¹        | ±1.8 % rH at 10 .. 90 % rH                                               |
|                                             | Air temperature (Swema 03: response time < 0.2 s)         | 10..40°C               | ±4.0 % rH at 0 .. 100 % rH                                               |
| Anemometer                                  |                                                         | 0.05 .. 3 m.s⁻¹        | at 20..25°C: ±0.03 m.s⁻¹ at 0.05 .. 1 m.s⁻¹                             |
|                                             |                                                         |                        | at 15..30°C: ±0.04 m.s⁻¹ at 0.05 .. 1 m.s⁻¹                             |
| Datalogger Ahlborn ALMEMO® 2590-4AS + 3 dual NTC input connectors ZA9040FS2 | Surface temperature sensor (Vishay NTCLE413)          | -50 to 125 °C          | ±0.1 K at 0 .. 30 °C                                                     |

Table 2. Selected scenarios for the investigation of condensed water formation on the panels.

| Scenario                        | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|---------------------------------|----|----|----|----|----|----|----|----|
| Mean panel surface temperature [°C] | 28 | 19 | 14 | 10 | 30 | 19 | 14 | 10 |
| Dew point [°C]                  |    |    |    |    |    |    |    | 16.8 |
| Air temperature [°C]            | 28 |    |    |    |    |    |    | 30  |
| Relative humidity [%]           |    |    |    |    |    |    |    | 40  |
Figure 2. Horizontal view (left) of the air velocity and air temperature measurement grid as well as the frontal view (right) of the radiant cooling panel with the location of the surface temperature probes (all dimensions in centimeter).

Figure 3. Illustration (vertical view) of the air velocity and air temperature measurement grid (all dimensions in centimeter).
2.2. Result

Figures 4 and 5 show the results of the near-panel air flow measurements. Figure 4 shows the air velocity at the selected positions (i.e., at different distances from the panel as well as at different heights). Figure 5 shows the measured air temperature at the same positions. In both Figures, a logarithmic scale is used to present the data. This was found to be informative especially in case of measured air speeds, given the large gradient of the measurements in close proximity to the panel. Note that the measurements of both air speed and temperature were conducted in the course of an approximately one-hour period. As noted already in the method section of the paper, the temporal variation of all measured variables during this period was found to be within acceptable ranges.

![Figure 4](image1.png)

**Figure 4.** Measured air velocities at multiple positions (target panel surface temperature: 10°C; ambient air temperature: 30°C; relative humidity 40%).

![Figure 5](image2.png)

**Figure 5.** Measured air temperature at multiple positions (target panel surface temperature: 10°C; ambient air temperature: 30°C; relative humidity 40%).
2.3. Discussion
The experimental investigation of the near-field air speed showed air velocities up to 0.2 m.s\(^{-1}\) in close proximity to the radiant cooling panel (see Figure 4). Once the distance between the panel and the measurement position exceeded 2 to 3 cm, the air velocity was clearly reduced. At several positions, the air speed was too low to be reliably detected with the deployed sensors. The highest air speed values were measured at a height of 10 cm above the floor. These results suggest that, for the tested conditions (specifically, panel surface temperature and air temperature) and at distances beyond 5 cm from the panel, air velocities induced purely due to convection are two low to have any implications for issues related to occupants' perceived draft or discomfort. Note that, at a distance of 20 cm from the panel and a height of 10 cm, an increase in the air velocity is visible. A reason for this result can be the fact that the 3 cm high edge of the condensed water collection container lies at a distance of 25 cm from the panel (see Figure 3). It is conceivable that this physical barrier could have influenced the air flow movement and thus contributed to the observed air velocity increase.

As the measurements of air velocities at each position was conducted over a certain period of time (roughly one minute), it was also possible to derive the turbulence intensity [6] at the same position. The obtained values of this index were slightly higher at the height of 10 cm above the floor. However, at distances beyond 3 cm from the panel, the values of this index are practically negligible, independent of the height of the measurement position and its distance from the panel.

Concerning the measured air temperature at different positions, we can observe a slight dependency on the distance from the panel, and a more pronounced dependency on the height above the floor. The temperature at the planned position of the occupant is approximately 2 K higher compared to the temperature at a distance of 5 cm from the panel. The vertical temperature difference at the occupant's positions is, however, higher. Put differently, at the occupant's position, the temperature at a height of 110 cm above the floor is approximately 4 K higher than at a height of 10 cm and thus slightly beyond the recommended maximum vertical temperature differences of 3 K [7].

Observations with regard to the formation of water vapor condensation showed that surface condensation occurred only in the situations in which the surface temperature of the radiant panel was below the dew point temperature (see scenarios 3, 4, 7, and 8 in Table 2). Nonetheless, even in these cases the magnitude of the occurred water vapor condensation on the panels was rather small. In fact, due to the ongoing re-evaporation of the collected water, no special water drainage functionality was required. Given this circumstance, routine surface cleaning measures as common in office spaces appear to sufficiently address any issues concerning the appearance and hygienic attributes of the proposed local radiant panels and respective containers.

Given the configuration of the pipes for the distribution of cold water through the panel, a certain variance of the surface temperature across the panel area is unavoidable. However, the measured panel surface temperatures at multiple points across the panel area displayed a reasonably low deviation from the mean, namely 0.7 K.

3. Conclusion
In this contribution, we explored certain performance issue of a previously introduced radiant cooling approach, which we referred to as occupant-centric. The underlying assumption is that vertical radiant panels in the close proximity of the occupants not only reduce the required cooling power, but – if properly configured – can also deal with potential water vapor condensation. Consequently, lower surface temperatures of the radiant panels can be maintained. In this paper, the results of a recent experimental examination of the air flow and temperature fields close to the radiant panels are presented. In this context, prototypical radiant panels were installed in two rooms of a laboratory and multiple experiments were conducted (ambient air temperature: 30°C, relative humidity: 40%). The outcome of the experimental investigation of the near-field air speed showed that, at very small distances to the radiant panel (below 5 cm), the air velocity is higher. Beyond this distance, the measured air velocity is significantly lower. Consequently, the results of the study do not point, even at the floor level, to any risk of draft or turbulence discomfort due to convection induced by the temperature gradient between
panel surface and ambient air. Moreover, neither the surface temperature variation across the panel, nor observed magnitudes of water vapor condensation appear to represent any notable hinderance toward the deployment of the proposed radiant panel solution.

Ongoing and future studies are intended to further explore the performance of local radiant cooling panels, particularly in view of their energy saving potential. Moreover, experiments involving a sufficiently large and representative number of participants are planned to evaluate, in more detail, the thermal comfort provision potential of these radiant cooling panels.

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