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Thermal comfort in buildings using radiant vs. all-air systems: A critical literature review

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ABSTRACT

Hydronic radiant heating and cooling systems are considered as an energy efficient technology to condition buildings. We performed a literature review to assess if radiant systems provide better, equal or lower thermal comfort than all-air systems. We included only peer-reviewed articles and articles published in proceedings of scientific conferences. The publications found have been classified based on research methods used. These include: (1) building performance simulation (BPS), (2) physical measurements (in laboratory test chambers and in buildings) and (3) human subject testing/occupant based surveys. This review identified eight conclusive studies: five studies that could not establish a thermal comfort preference between all-air and radiant systems and three studies showing a preference for radiant systems. Very few studies were based on occupant feedback in real buildings suggesting a significant research need. Overall, we found that a limited number of studies are available and therefore a solid answer cannot be given. Nevertheless, there is suggestive evidence that radiant systems may provide equal or better comfort than all-air systems.

1. Introduction

Hydronic radiant heating and cooling systems are considered as an energy efficient technology to condition buildings. They are seen as a market ready alternative to conventional all-air systems to help achieve up to 50% reduction in primary energy use in buildings [1–3]. In addition, radiant systems are also commonly associated with improved thermal comfort in comparison to all-air systems. The objectives of this critical literature review are to (1) verify this assumption and identify whether radiant systems are providing better, equal or lower thermal comfort compared to all-air systems, and (2) determine which thermal comfort assessment method is the most relevant to compare the two systems.

While the first examples of radiant systems (using hot air as medium) go as far back as the 11th century B.C. in Korea [4], studies of these radiant heating and cooling applications in terms of thermal comfort waited until the 20th century. This interest started in Europe and was focused on subjective impressions of warmth and freshness [5], on theoretical heat perceived at head level [6], and on thermal sensation and skin temperature of feet for radiant floors [7]. The data from these studies were further analysed to define comfort requirements for both radiant floors and ceilings [8]. This work on thermal comfort for radiant systems caught the attention of researchers at Kansas State University who then started an extensive research program on radiant systems for heated and cooled floors [9–13], and on the effect of asymmetrical conditions [14–18]. In Denmark, Fanger and Olesen contributed to this effort by investigating the limitation of radiant systems at providing homogenous (isothermal) thermal environments [19–21]. These studies were based on human subject testing in laboratory chambers and were oriented towards guidelines to avoid potential sources of discomfort identified as temperature asymmetry, vertical temperature gradient and floor surface temperature. The practical implications of these studies are included in thermal comfort standards [22,23].

Researchers have used theoretical arguments to justify why radiant systems can provide better comfort than all-air systems. The main arguments are: reduced air movement and draft problems [24,25], active control of mean radiant temperature (MRT) [26–28], more homogeneous conditioning provided to the space [25,29], positive influence on the human 'body-exergy' balance for both radiant heating and cooling cases [30], and comfort for floors systems due to highest view factor to the occupants [31]. Sometimes, researchers have referred to many of these arguments

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[32–36]. While these arguments are reasonable, they fail to provide clear evidence on improved thermal comfort for radiant compared to all-air systems. Additionally, both radiant and all-air systems comprise a variety of types, strategies and design. Radiant systems need to be combined with a ventilation strategy to fulfil fresh-air requirements. All this adds complexity to the comfort assessment of the two systems.

This paper presents the results of a literature review on thermal comfort for radiant vs. all-air systems. After a brief description of the thermal comfort metrics commonly used for this comparison, we will detail the studies found based on the methods used. This review also questions the relevance of the methods used and highlights research needs. Beyond the comparison, we will address a few more concerns and findings regarding thermal comfort for radiant systems.

2. Methods

We performed a literature search using the key terms: "thermal comfort", "radiant systems", "hydronic systems", "thermo-active building systems", "thermally activated building components", "concrete core slab", "concrete core conditioning", "thermally activated building systems", "in-slab heating, floor surface radiant systems, radiant panel, low temperature heating and high temperature cooling systems", "chilled ceiling" and "water-based floor heating" in the following databases: Google Scholar and Web of Knowledge. We also used the reference sections of the papers we gathered to find additional publications. Selected proceedings, conference papers were also screened. We included only peer-reviewed articles and articles published in proceedings of scientific conferences. We excluded from our final selection all the publications that were based on grey literature or not comparing radiant to all-air systems.

We decided to classify the publications based on the research methods used: (1) building performance simulation (BPS), (2) physical measurements (in laboratory test chambers and in buildings) and (3) human subject testing/occupant based surveys. We use this classification scheme because it allowed us to distinguish simulated, measured and subjectively perceived comfort. When one article had more than one method, we decided to classify the publication based on the most robust method used (see discussion section for the comparison of the different methods).

3. Classification scheme

3.1. Review of the metrics used to assess thermal comfort

In ASHRAE Standard 55-2013 [22], thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment". This definition brings forward the delicate question of which metrics can be used to assess thermal comfort. In this section we go over the comfort metrics that are relevant for our review. These include the metrics we came across during our literature review as well as the key comfort metrics used in radiant systems assessment. Metrics are classified into two categories: objective metrics (based on physical measurements) and subjective metrics (based on occupant feedback).

3.1.1. Objective metrics

One common way to quantify thermal comfort is through the measure of dry-bulb air temperature, globe temperature, mean radiant temperature (MRT) (derived from the globe temperature), and operative temperature (calculated using dry-bulb air temperature and MRT). The globe temperature also exists as 'half-globe' accounting for only half of the space.

The predicted mean vote (PMV) is a comfort model established to predict thermal sensation from "cold" to "hot" [84]. This objective metric was developed using human subject testing in laboratory conditions and is based on a heat balance model applied to the human body. It uses six parameters: dry-bulb air temperature, MRT, air velocity, relative humidity, clothing level and metabolic rate and ranges from -3 (cold) to $+3$ (hot) with the value of 0 set as neutral. This metric has been translated into a predicted percentage of dissatisfied (PPD). Highest thermal comfort (i.e. lowest PPD) is associated with a neutral body sensation (PMV of 0).

The range of indoor conditions (e.g., temperature dead band or PMV/PPD values) can be used to characterize thermal comfort. EN ISO 7730 [23] and EN 15251 [37] are using this method to define three categories of thermal requirements for mechanically cooled buildings: category I (or class A) (PPD < 6%, i.e. $-0.2 < PMV < +0.2$), category II (or class B) (PPD < 10%, i.e. $-0.5 < PMV < +0.5$) and category III (or class C) (PPD < 15%, i.e. $-0.7 < PMV < +0.7$). To account for time, EN ISO 7730 and EN 15251 propose frequency of exceeding a given category in percent time. There is some debate about the interpretation of these categories as aligned with levels of thermal comfort quality [38,39]. Large field experiments have shown that the tightly air-temperature-controlled space (class A) did not provide higher acceptability for occupants than non-tightly air-temperature-controlled spaces (class B and C) [40]. Based on these arguments, ASHRAE 55 [22] did not include the classification of building categories. Yet, this metric was often used in the papers found for this review.

We found four local discomfort factors that are particularly relevant for radiant systems:

(1) Radiant asymmetry is defined as difference between the plane radiant temperature of the two opposite sides of a small plane element [20]. It is usually measured using half-globes to compare temperatures of two opposing surfaces of a room. Both EN ISO 7730 [23] and ASHRAE 55 [22] define limits of radiant asymmetry when using radiant walls, floors and ceilings. These limits originate from Ref. [21] and are based on a percent dissatisfied curve.
(2) Floor temperature that may be too low or too high can cause discomfort. Therefore, international standards have defined intervals of recommended temperatures based on a percent dissatisfied curve. EN ISO 7730 [23] and ASHRAE 55 [22] specify limits for rooms occupied by sedentary or/and standing people wearing shoes. Both standards recommend floor surface temperatures within the occupied zone to be kept between 19 °C and 29 °C.
(3) A high vertical air temperature difference between head and ankles (stratification) can cause discomfort. [41] have established a correlation between vertical air temperature difference between head and ankles ($PD_{vertical}$) that has been further spread through the EN ISO 7730 [23] and ASHRAE 55 [22]. This metric only applies for head temperature being higher than feet temperatures (people are less sensitive under opposite conditions).
(4) Draft is defined as an unwanted local cooling of the body caused by air movement. [42] developed a draft model using three variables (air temperature, mean air velocity, and turbulence intensity). Based on human subject testing this model was converted into percentage of dissatisfied for draft (PD_{draft}). This index is further defined within the EN ISO 7730 [23] but it has been removed from ASHRAE 55 because it was found to overestimate the draft risk [43].

Another discomfort metric related to non-steady-state thermal environments is the 'temperature drift'. This metric is defined as a steady, non-cyclic change in operative temperature of an enclosed space. Temperature drift is associated with discomfort and is reported in [K/h]. Standard EN ISO 7730 [23] allows a maximum drift of 2 K/h. ASHRAE Standard 55 [22] allows for 2.2 K/h for drift duration of 1 h, but not more than 2.6 K/h during any 0.25 h period within that 1.0 h period. ASHRAE 55 also requires drift lasting 4 h to be reduced to 0.8 K/h.

Human physiological measurements could also be taken. In our review, we found laboratory studies focusing on the different body part temperatures. These measurements are usually done according to standards (e.g., EN ISO 7726 [44]). Physiological measurements may also include core body measurement using an ingestible telemetry pill. These measurements can be used as input to detailed comfort models (such as the Advanced Thermal Comfort Model [45]), which can then be used to predict local and overall thermal comfort.

3.1.2. Subjective metrics

Thermal sensation vote (TSV) is a scale to rate thermal sensation from “cold” to “hot”. Vote refers to human subjects filling out a thermal sensation scale during the exposure to certain thermal conditions at a given point in time. This metric was used to develop the PMV index and is sometimes referred to as ‘actual mean vote’. Most researchers use a continuous 7-point ASHRAE interval scale going from −3 (cold) to +3 (hot) with the value of 0 set as neutral [22]. TSV can be conducted for whole body (global) sensation as well as for local sensation. The latter allows a comparison with the physiological measurements of local body parts.

Thermal comfort vote (TCV) is a scale to rate thermal comfort from “uncomfortable” to “comfortable”. This vote requires human subjects or building occupants to fill out a thermal comfort scale. We commonly find this metric in right-now survey (at a given point in time) or background surveys (in general). This vote is commonly set on the ISO-defined 4-point scale (“uncomfortable”, “slightly uncomfortable”, “slightly comfortable”, “comfortable”), where the value of 0 is unavailable [46]. We however found in our review a publication using a 5-point scale that included a “neutral” comfort vote [47]. TCV can be conducted for whole body (global) as well as for local body parts.

Occupant satisfaction votes are often conducted in the framework of indoor environmental quality (IEQ) surveys in buildings. Typical questions on thermal comfort include satisfaction with temperature and self-reported performance/productivity in relationship to temperature. These surveys usually use 5- or 7-point scales ranging from “(very) dissatisfied” to “(very) satisfied” and with the value of 0 set as neutral (e.g., CBE Occupant IEQ Survey [48]). Additional subjective metrics on thermal comfort include thermal preference and thermal acceptability. Yet we did not come across these metrics in our review.

3.2. Conditioning systems classification

The terminology used for the various radiant and all-air systems is not always consistent across publications. In order to ease and better compare the systems, we decided to use a common classification scheme based on the current standards and construction of the systems.

3.2.1. Types of radiant systems

By definition, radiant systems provide at least 50% of the total sensible heat flux for space conditioning by thermal radiation. We looked at the international standard ISO 11855 [49], the European standard EN 15377 [50], the ASHRAE Handbook on HVAC Systems and Equipment (chapter 6) [51] and the REHVA guidebook [52]. Based on these standards and guidelines, we identified three main types of radiant systems: (1) radiant panels, where the pipes are attached to metal panels which are fixed to the construction by means of hangers [51,52]; (2) embedded surface systems (ESS) where the pipes are embedded in the surface of the slab/wall, but are insulated from the structure (EN 15377/ISO 11855, type A, B, C, D, G), and (3) thermally activated building systems (TABS), where the pipes are embedded in a massive concrete slab/mass (within the structure) (EN 15377/ISO 11855, type E). In our review, we classified the systems according to these three types (see Fig. 1) and will report the surface activated (floor or ceiling).

3.2.2. Types of all-air systems

In an ‘all-air system’, the extraction rate is mainly convective. While we found a few publications referring to natural ventilation (NV), most articles compared radiant to buildings that include a mechanical ventilation systems (MV). In some cases, both natural and mechanical ventilation could be activated (hybrid ventilation systems). Many studies are about cooling conditions in which case, the air system is more commonly referred to as ‘air-conditioned’ (AC). MV can be further characterized by the design of air distribution strategies, that can have a large impact on the thermal comfort. We identified 3 common types of all-air distribution strategies:

- Overhead (or mixing systems): supply air is delivered at a high velocity outside the occupied zone, usually at the ceiling level (overhead).
- Underfloor air distribution (UFAD): supply air is delivered from a raised access floor through floor diffusers that provide partial mixing of the room air, typically confined to the occupied zone.
- Displacement ventilation (DV): supply air is delivered within or close to the occupied zone (at or near the floor level). DV is sometimes classified as a subcategory of UFAD. What distinguishes the two systems is that DV does not necessarily require a raised access floor (air can be supplied through low side-wall diffusers) and the DV inlet velocity is very low to minimize mixing.

Chilled beams are a combined hydronic/air system that uses convection as the primary heat transfer mechanism. Thus and because this review focuses on thermal comfort, we decided to classify chilled beams as an ‘all-air’ system.

4. Comparison of the systems

Of the 73 papers reviewed, 53 papers were excluded: 29 were not based on an actual comparison between the two systems; 16 were ‘earlier studies’ on thermal comfort for radiant systems (they were used to establish thermal comfort criteria and the testing conditions were beyond what is currently recommended); four were focused on exergy aspects without digging much into thermal comfort for the two systems; two were on transient conditions (rather than on radiant); one was not peer-reviewed.

and one did not provide a proper description of the method and assumptions used. Of the remaining 20 papers, eight were judged conclusive (e.g., fair and realistic in the assumptions or laboratory set-up, comfort models used to assess the two systems).

4.1. Studies using building performance simulation

We found 9 papers comparing thermal comfort in radiant versus all-air systems that were based on computer simulation programs. Among the software used, we found: computational fluids dynamics (CFD) (e.g., Fluent) able to simulate the detailed airflow patterns and temperature distribution within the space, and whole

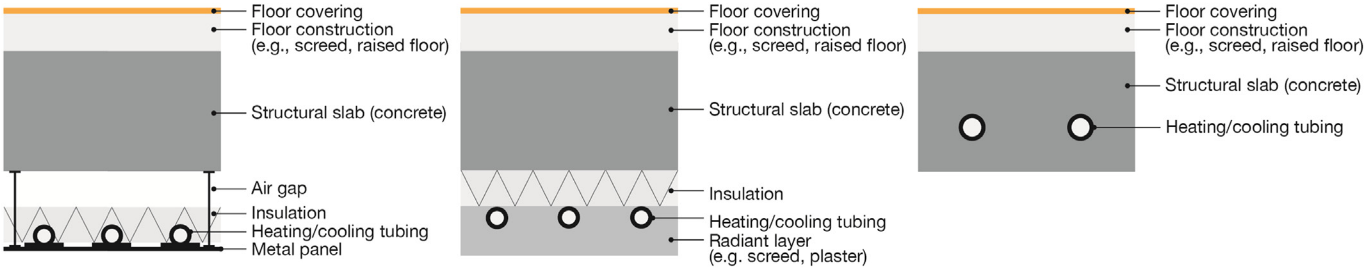

Fig. 1. Illustration of radiant panels (left), embedded surface systems (ESS) (center) and thermally activated building systems (TABS) (right).

building energy simulation (e.g., EnergyPlus [53] or TRNSYS [54]) used to model zones and systems and predict indoor conditions and energy use for buildings. [55] used CFD to assess thermal comfort for radiant in comparison to all-air systems. They used vertical temperature distributions (stratification) and PD_{draft} as the main metrics. No clear preference for either system was found based on the two metrics. Building energy simulation offers researchers an effective method to simultaneously investigate thermal comfort and energy consumption in buildings. In many cases, the papers compared energy use under equivalent comfort conditions between the multiple radiant and all-air variants [56–60]. These studies were not retained as they focused on energy savings given thermal comfort constraints. Three studies using building energy simulation had a larger focus on thermal comfort and how this could satisfy our requirement for the selection of articles as described above. Chowdhury et al. [61] reported the study of the existing building located in Queensland Australia using a VAV system with air-conditioning (AC) and three low-energy upgrade variants: radiant ceiling panels (33% ceiling area), economizer and pre-cooling (cooling of the thermal mass through air-conditioning during off-peak hours). In all cases, the existing mechanical ventilation system is retained, but the strategies to cool the building are different. All simulations were conducted using DesignBuilder (with fine-tuning on EnergyPlus). The metric used was the PMV model. Although the radiant system appeared as the most comfortable of the three refurbishment options, the results showed that it did not bring thermal comfort improvement in comparison to the original AC system: the two systems would bring equivalent comfort. Overall, we found that this study did not bring conclusive evidence for improved thermal comfort for either system: the goal of the study was to find the best refurbishment variant and the PMV output was highly dependent on simulation input. Olesen and Mattarolo [62] used EnergyPlus to compare ten different radiant system configurations (TABS, radiant panel, and ESS located on either floor or ceiling) to a reference (conventional) variable air volume (VAV) system with active heating and cooling. The simulation was done for a 4-story building located in Copenhagen, Denmark. The comfort metric used was the percentage of time during which indoor conditions (operative temperature) falls within categories I and II of EN15251 [37]. It was concluded that all radiant system variants enhanced the thermal comfort conditions. Yet, the input details of the simulations variants (including geometry of the building zones, controls, description of the radiant types, etc.) have not been provided in this conference paper. Also we could not track a more robust journal publication version of this paper. Therefore, we decided not to include this paper among the conclusive references. Salvalai et al. [63] used TRNSYS to compare five cooling strategies for a typical office for six different European climates. Radiant strategies included suspended ceiling panels and TABS (both combined with MV). All-air systems included a MV with fan coil. Additional passive based variants included NV and MV with night time ventilation cooling. The metric used to compare the variants is the percentage of time during which indoor conditions exceed the comfort limit of category II. For colder climates (represented by the cities of Stockholm, Hamburg and Stuttgart), both radiant and fan coils were within the standards requirements. For warmer climates (cities of Palermo, Rome, Milan) radiant systems variants could stay below 10% exceedence, while the fan coils variant reached approximately 35% in the worst case (Palermo). This study shows favourable thermal comfort for radiant systems compared to air systems. Yet we note that the scenario using radiant panels and TABS were assessed using the adaptive approach (based on EN 15251 [37]) while the fan coil was assessed using the static approach (based on ISO 7730 [23]). Radiant panels and TABS were here combined with a MV system (and not a NV) and using the adaptive comfort model may not be totally correct for a fair comparison. Furthermore, it seems unlikely that a properly sized fan coil would bring this level of exceedence in the warmer climates. Based on these limitations, we found this study was unfair for our comparison purposes. From all studies based on BPS we thus retained one publication that did not show a clear preference for either systems [55].

4.2. Studies based on physical measurements

4.2.1. Studies involving physical measurement in laboratory conditions

We found five studies comparing radiant and all-air systems that were fully or partially based on physical measurement in laboratories. Olesen et al. [64] conducted a full-scale experiment of a small office with one simulated outside wall. Nine heating systems were tested, including: radiant ceiling, radiant floor (electric system with an aluminium plate used for uniformity), air distribution system (different diffusor positions, air velocity in the room, air changes and air temperatures), convectors, radiators. The chamber included an adjacent controlled space that could simulate winter conditions through an outside wall (temperature down to −5° C and air infiltration rates up to 0.8 air-changes/h). The heat input was adjusted so that the room reference point nearby the frontage (assumed to be the most common place for an occupant to be seated) showed thermal neutrality. During steady-state conditions, air temperature, air velocities and surface temperatures were measured at several points. All nine heating systems proved in all tests to be capable of creating a remarkably uniform thermal environment (PPD ~ 5%) in the entire occupied zone. The vertical air temperature difference between 1.2 and 0.1 m level was less than 1.8K in the whole occupied zone in all tests. The floor temperature in the occupied zone with floor heating was always less than 27.5 °C. It was concluded that all nine heating methods investigated are able to create an acceptable thermal environment. Kulpmann [65] performed thermal comfort and air quality experiments in a laboratory chamber equipped with a radiant ceiling and DV system.

The internal loads were simulated through lighting and two workstations (thermal manikin and computer displays). The authors investigated the effect of varying the cooling capacity shares of the cooled ceiling and the ventilation system. The vertical profile of the room temperature was more pronounced when the load was covered with the ventilation system. An uncomfortable temperature difference of 5 °C between ankle (0.1 m) and head (1.7 m) was measured when only DV was active. Little to no stratification was observed when the cooling load was handled (mainly/fully) by the radiant system. Air quality investigation showed that combination of DV with cooled ceiling induced a mixing of air within the space and could not ensure a safe displacement of air-transported pollution into the respiration area. Overall, the authors concluded that a cooled ceiling surface was 'best qualified' to maintain thermal comfort. Schiavon et al. [66,67] tested a similar combination a radiant ceiling and DV. In the first paper, they tested two different radiant coverage areas of the ceiling in addition to a baseline with only DV. The experiment was set up to keep the operative temperature fixed at 24° C for all configurations tested. For the pure DV test, the temperature profile suggests that the stratification height is between 1.1 m and 1.7 m. When the chilled ceiling was turned on, the stratification height appears to be reduced to a height close to 0.6 m (23 in.). The authors also observed that room air stratification in the occupied zone decreases when a larger portion of the cooling load is removed by the chilled ceiling. In all cases, we note that the temperature difference between head and ankle stayed below 3° C which satisfies standards requirements. It is thus delicate to conclude on one system achieving a better comfort. In the second paper, the same authors investigated the influence of very high cooling load (91 W/m^2) and two different heat source heights on thermal stratification (and air change effectiveness). The DV was tested for the higher heat source height only. Increased stratification was observed in the case of DV only compared to DV and radiant scenarios. The temperature difference between head and ankle exceeded standards requirements for the DV only case as well as for some of the DV and radiant combinations. While this experiment could bring some evidence for increased comfort in favour of the radiant system, we shall point out the very specific setting with high internal loads at a certain height. Such indoor layout seems quite specific and thus we will not include this result for our final assessment. Corgnati et al. [68] used a combination of experimental and numerical methods to assess an all-air mixing ventilation system alone or coupled with radiant ceiling panels in an office environment. The comfort metrics were related to the risk of draft (including PD_{draft}). The experiment was used to validate the CFD model. The radiant system was not part of the experimental set-up. The results showed that coupling air mixing and cold radiant ceiling panels with air jet supplied at low Archimedes numbers improves comfort in comparison to a system without radiant panels. The radiant cooling panels are increasing the jet longitudinal throw and reducing the vertical drop. This brings a significant decrease of the PD_{draft} due to the jet direct drop for the radiant configuration. Although this study shows an advantage for the radiant system variant, we decided not to include this study within our final count because it refers to a combination with a very specific air systems and because the metric used for the analysis (PD_{draft}) may overestimate discomfort. Mustakallio et al. [69] studied thermal comfort conditions of a 17.3 m^2 room (modelled as a 2-person office and as a 6-person meeting room) including thermal manikins, two types of internal loads (medium and high) and a façade with a window. Four cooling variants were tested: (1) radiant panels with mixing ventilation using two linear diffusers located right below the radiant ceiling; (2) radiant panels with chilled beams using suspended radiant panels centred above the desk area, (3) chilled beam, and (4) mixing ventilation with desk-integrated cooling radiators. For consistency, we do not account the last variant as the system modelled is not a traditional radiant system (see Section 3.2.1). Chilled beams (without radiant) use convective heat exchange and are here classified as an all-air system (see Section 3.2.2). Results showed that the differences in thermal conditions achieved across the variants were not significant. The type and location of the diffusors in variant 1 bring questions regarding the primary heat exchange (convective or radiant) involved. Variant 2 remains radiant and therefore we decided to keep this study for our final assessment.

From all studies based on physical measurements in laboratory settings we thus retain two lab testing of multiple systems in heating mode that showed comfortable conditions for both all-air and radiant systems [64,69] and one experiment of a DV system combined with a radiant chilled ceiling making a positive case in favour of radiant systems [65]. We include further laboratory studies based on both physical and human subject testing in Section 4.3.1.

4.2.2. Studies involving physical measurement in buildings

Field-studies based on both objective and occupant-based feedback are reported in Section 4.3.2. Pfafferott et al. [70] studied 12 low energy buildings located in Germany that included 4 buildings with thermally activated building systems (TABS). No buildings in this study had a compressor-based chiller. Cooling strategies include night ventilation for pre-cooling and earth-to-air heat exchangers. The indoor monitoring of thermal conditions was conducted over 2–3 years (between 2001 and 2005) in each building. This study was aimed at comparing the thermal comfort output of international and German standards and not comparing radiant to other conditioning systems. Therefore, the results may be considered carefully. The metric used was the frequency of exceeding standard requirements. The results showed the lowest frequency of exceeding for buildings using TABS in comparison to NV or hybrid systems (none of the buildings of this study were fully mechanically ventilated). This study was however not intended towards a comparison of conditioning systems and it would require specific analysis on that aspect to be able to draw conclusive answers on thermal comfort. Therefore, we will not include its result for our final assessment. Besides this study, we found multiple case-studies based on physical measurements in buildings and focusing on thermal comfort for radiant systems (e.g. [71–74]). These studies commonly show positive results in regard to thermal comfort in radiantly conditioned buildings. Yet none of these studies included a comparison of thermal comfort between radiant and all-air systems. To conclude, we won't retain any studies based on physical measurement in buildings for our final assessment.

4.3. Human subject testing/occupant based surveys

4.3.1. Studies involving human subject laboratory experiments

We found two laboratory studies involving human subjects directly comparing radiant and all-air systems [75,76]. In the first study, Schellen et al. [76] wanted to focus on gender differences in thermophysiology, thermal comfort

and productivity during convective and radiant cooling. Twenty college-age subjects (ten female and ten male) were exposed to the two cooling systems consecutively: convective and radiant. All tests were kept at neutral and comparable PMV levels. The results showed that under non-uniform conditions, the thermal sensation votes (TSV) significantly differ from the PMV: all tests showed a difference of 0.4–0.6 on a 7-point scale ($p < 0.001$) for both conditioning systems and genders (this represents a change in PPD of about 10%). The experiment was conducted over a 4-h testing period and the authors found that for females the occupant responses changed over time for both radiant and convective conditioning. While the authors found different explanations for the time effect of the two conditioning systems, they concluded that radiant and air systems are equal in their ability to provide comfort. Overall, this study did not show preferences for either radiant cooling or all-air cooling systems. In the second study, Schellen et al. [75] directly addressed the comparison of radiant and convective cooling systems. The authors explored three all-air scenarios: mixing ventilation with increased air velocities (no active cooling for this first configuration –all other configurations include active cooling), mixing ventilation, displacement ventilation; and three radiant scenario: radiant ceiling with mixing ventilation, radiant floor with mixing ventilation, radiant floor with displacement ventilation. Ten college-age male subjects were exposed to all six conditions during a 2 h testing period. All tests were kept at neutral and comparable PMV levels. The difference between PMV and TSV stayed within the accuracy of 0.5 (except for the passive cooling variant). Based on the physical skin temperature measurements, the authors noted that these differences between PMV and TSV were likely to be caused by local effects and local discomfort. The highest TSV was observed for the radiant floor cooling cases (with a floor temperature measured at 19.5–20 °C against roughly 24 °C for all-air cases). Subjects voted highest thermal comfort for active cooling by both displacement ventilation alone and chilled floor with displacement ventilation (75% of the votes for ‘comfortable’) and lowest thermal comfort for the passive cooling variant (increased air velocities) (55% of the votes differed from ‘comfortable’). This study showed that vertical temperature gradients (up to 4 °C/m) and lower temperatures near the floor even in combination with radiant floor cooling can result in acceptable thermal conditions. With respect to ventilation strategies, a clear preference was found for displacement ventilation. This study showed that non-uniform environments can achieve comparable or even more comfortable conditions compared to uniform environments. Yet, it did not prove preferences for any of the two (radiant or convective) systems. From all studies based on human subject laboratory experiments we retain two studies that could not show a preference for either system [75,76].

4.3.2. Studies involving occupant surveys

We found one study by Imanari et al. [47] comparing a radiant to an all-air system based on occupant feedback and simultaneous indoor condition monitoring. The comparison was performed in a meeting room of a building in Tokyo, Japan. This meeting room was built to include radiant ceiling panels and an overhead ventilation system (with and without reheat). The air change was double in the case of the all-air experiments (7.7 against 3.8 ACH for radiant panels for the same air supply and intake diffusers in the room), and therefore the air speed can be expected to be higher. Male and female experiments were conducted separately. For males, the room was used during a normal meeting and the subjects were asked to complete a thermal comfort survey at the end of their meeting (after a minimum stay in the room of 1 h). For females, the room was used for the purpose of the experiment; the testing time was longer (2 h) and the questionnaire included thermal comfort, thermal sensation (both at regular intervals) and work performance (measured through accuracy and achievement testing). Both males and females were tested under radiant and all-air conditions. Three series of experiments (for a total of seven cases) were tested. Males were tested for both cooling and heating cases; females were tested for cooling only. The number of subjects varied with each experiment. The PMV for all 3 series of tests was set at comparable levels and close to neutral. The results of this study showed a higher thermal comfort for radiant systems, more neutral thermal sensation votes for radiant and slightly improved work efficiency under the environment created by the radiant cooled ceiling. The draft risk measured in the room was also much smaller for the radiant cases (PD_{draft} estimated at 4.4–5.6% for radiant tests and 7.8–12.7% for all-air tests). This difference is likely to be associated with the sizing of the air system. As the draft risk metric has been rather criticized in our assessment so far, we decided to keep this study among the conclusive ones. We found the set-up involving an office with occupants relevant and decided to keep this study among the conclusive ones. Moving towards full building scale, the building “Software Development Block 1” (SDB-1), completed in 2011 located in Hyderabad, India offered a pretty unique setting as it is divided into two equivalent halves that comprise two optimized cooling systems: a mixing ventilation system (variable air volume (VAV) system) and a TABS with mixing ventilation (dedicated outdoor air system (DOAS)). The case study article from Sastry and Rumsey [77] included two thermal comfort aspects: objective measurements using a portable cart (dry-bulb air temperature, relative humidity, air velocity, MRT) and occupant feedback based on the Indoor Environmental Quality Occupant Survey developed at UC Berkeley [48]. Objective comfort measurements showed that the radiant side of the building had a PPD rating of 7.9% as compared to 8.7% for the VAV portion of the building (based on the EN ISO 7730 [23]). Both sides stayed at a pretty high level of predicted thermal comfort with a slight advantage for the radiant side. Yet, the publication did not inform us on the measurement details and resolution. About 150 occupants answered the survey on each side of the building. The survey results showed that the group that fell in the “satisfied” or “very satisfied” categories grew from 45% on the VAV portion of the building to 63% on the radiant portion. As a side note, energy use was found to be lower on the radiant side (34% less energy as compared to the VAV system based on the first two years of operation). This study is the only one we found involving such a side-by-side comparison. From all studies based on occupant surveys in buildings, we retain one study showing increased thermal comfort in favour of radiant system [77].

4.4. Summary of the comparison

Table 1 summarises the conclusive studies found in this comparison. One study using BPS brought comparable thermal comfort results for thermal comfort in all-air vs. radiant systems [55]. One study using physical measurements in laboratory conditions showed that a chilled ceiling with DV offers improved comfort compared to DV only [65]. Using the same method, [64,69] did not find increased comfort for either radiant and convective systems. Rigorous laboratory studies from Schellen et al. [75,76] did not prove preferences for either of the two systems. The study from Imanari et al. [47] showed a thermal preference for radiant systems. A building case-study reported by Sastry and Rumsey [77] used both physical and subjective measures to assess thermal comfort in the building. The results showed that the radiant side of the building is able to provide improved comfort conditions in comparison to the all-air side. In summary, this literature review identified five studies that could not establish a thermal comfort preference between all-air and radiant systems and three studies showing a preference for radiant systems. The methods used to demonstrate this were multiple and so were the types of all-air and radiant systems tested.

5. Discussion

5.1. Relevance of the methods used and future research

This critical literature review covered a wide variety of metrics and methods used to assess thermal comfort. We noticed that

Table 1
Summary of conclusive studies for our thermal comfort comparison.

Publication	Method	Cond. mode	Radiant system	Convective (all-air) systems	Preferred system
Niu and Kooi [55]	BPS	Cooling	Radiant ceiling panels with DV	DV, ceiling "air panels"	No preference found
Olesen et al. [64]	Lab testing (measurements)	Heating	Radiant ceiling, radiant floor	Convectors, Mixing ventilation (air supplied from the top and down nearby the façade)	No preference found
Kulpmann [65]	Lab testing (measurements)	Cooling	Radiant ceiling panels with DV	DV	Radiant
Mustakallio et al. [69]	Lab testing (measurements)	Cooling	Radiant ceiling panels with chilled beams	Mixing ventilation, chilled beams	No preference found
Schellen et al. [76]	Lab/Human subject testing	Cooling	Radiant ceiling panels with mixing	Mixing ventilation	No preference found
Schellen et al. [75]	Lab/Human subject testing	Cooling	Radiant ceiling panels with DV and mixing ventilation	Mixing ventilation, DV (multiple conditioning strategies)	No preference found
Imanari et al. [47]	Occupant surveys	Heating and cooling	Radiant ceiling panels combined with mixing ventilation	Mixing ventilation	Radiant
Sastry and Rumsey [77]	Physical measurements and occupant surveys	Cooling	TABS	Mixing ventilation	Radiant

metrics and models are often embedded and limited by the methods used. For instance, the PMV/PPD can be computed based on simulation output and can be physically measured. On the other side, subjective assessment requires human subjects or occupants. Thus, metrics, models and methods cannot be totally isolated from each other. We further found that the different methods were not offering us the same level of relevance in terms of thermal comfort assessment. We found that simulation-based methods are great to predict and compare variants and to verify standard compliance. Yet they are based upon the assumptions of idealized models, including the limitations of the comfort model used. Physical measurements are fundamental to verify indoor conditions and monitor buildings, but they often are unable to provide feedback on how a particular type of system impacts perceived comfort. Thus, we found that studies involving human subject testing and occupant based surveys were the most relevant for assessing thermal comfort.

Human subject testing in laboratories allows researchers to precisely control indoor conditions and assess perceived comfort at a great level of detail based on both objective and subjective metrics. On this aspect the laboratory studies from Schellen et al. [75,76] were particularly relevant. They did not predict significant differences between the whole-body and body-part comfort levels. This outcome addresses the common perception of a non-uniform thermal environment being less comfortable than a uniform one. The fact that these studies did not conclude on a preference for either system is pretty informative.

Field studies do not allow the same level of control as laboratory studies but they provide evidence of how building systems perform under realistic and practical conditions. Results from occupant based surveys ultimately provide feedback on what buildings, systems, and other aspects of their indoor environment do occupants prefer compared to others, which is a key aspect for successful implementation of building technologies. Yet, occupant survey studies also incorporate one key limitation: they rely on subjective answers collected while many uncontrolled variable change at the same time and thus larger samples are required to overcome singularities and to capture responses of average occupants. The case of SDB-1 brought a strong case for the thesis that radiant systems provides better thermal comfort than air systems, but only one example of this comparison is available.

Comparing multiple cases of radiant buildings against multiple cases of non-radiant buildings may offer us a very relevant method to assess thermal comfort in real conditions. This method was used in Brager and Baker [78] when comparing mechanically conditioned and mixed-mode buildings or by Altomonte and Schiavon [79,80] when comparing LEED to non-LEED buildings. This method seems extremely appropriate for bringing new answers to our question and it does not require buildings to be built as a side-by-side comparison. In fact, there are plenty of radiant and all-air systems within the existing building stock from which we can learn and that potentially offer us many resources. Because buildings tend to be different from each other (and not only based on the mechanical systems) we need to isolate confounding factors and therefore there is a need to conduct a large sample assessment. These studies will help us identify thermal comfort satisfaction patterns, and thus, provide answers to our questions while taking into account the practical constraints and robustness of HVAC system implementation and operation as well as the influence of further design aspects on thermal comfort.

A more general limitation of this review is the multiplicity of systems and conditioning strategies involved in both radiant and all-air cases. All-air systems comprised stratified and mixing systems; radiant systems included metal ceiling panels and TABS ranging from partial to full covering of surfaces, and located on both floors or ceilings. Additionally, radiant systems are required to be supplemented with a ventilation strategy, typically a dedicated outdoor air system. Both systems were tested under heating and/or cooling conditions at different supply temperatures. However, in our simplified classification scheme, the 19 studies we retained for our final analysis investigated over 20 different systems and associated controls. This variability adds noise within our assessment. It seems that multiple systems (including both radiant and all-air) are able to provide acceptable thermal comfort, depending on several factors, including operation and control.

5.2. Additional observations on thermal comfort for radiant systems

5.2.1. Temperature drifts for massive radiant types

Our final selection of publications did not include studies using temperature drifts because we could not find a paper comparing radiant to all-air systems that would be based on this metric. Temperature drift is still believed to be an issue for radiant systems that incorporate high thermal mass (e.g., TABS). During warm days these massive systems absorb heat until saturation. As a result, the rising temperature towards the end of the day may exceed the upper boundary of the comfort zone. Kolarik et al. [74] conducted a study of three European buildings using TABS located in Spain, Italy and Denmark. Physical measurements showed that the limit for 4-h operative temperature drift (0.8 K/h) was exceeded in all buildings. While temperature satisfaction slightly decreased when the rate of temperature change increased, the median value of these votes stayed positive ("satisfied" and "just satisfied") even for the most extreme drifts. The authors reported that the data collected did not allow for robust statistical analysis. Thus, additional field studies would be needed to validate or challenge previous laboratory studies that did not include a radiant system (artificially controlled drifts) and where occupants were not allowed to modify their clothing during drifts [81].

5.2.2. Applicability of the human body exergy concept

The human body exergy concept is based on the assumption that one reaches thermal comfort when one's metabolic emission equals the energy outflow (due to radiation, convection, evaporation, conduction). Thus, having an influence on the mean radiant temperature increases the chances to target lowest human body exergy by design. Simone and Olesen [82] conducted a human subject laboratory experiment to address this question. 30 subjects were exposed to three different combinations of air and mean radiant temperature with an operative temperature around 23 °C. Yet this study could not confirm any preference regarding air and mean radiant temperature ranges. Using multiple datasets from radiant system laboratory studies [14,16,17,82], Simone et al. [83] further investigated the relationship between thermal sensation (used as proxy of thermal comfort) and human body exergy consumption. Their statistical analysis showed that the lowest human body exergy was correlated with neutral and slightly cool thermal sensations, yet with a moderate correlation coefficient ($R^2 = 0.68$), regardless the fact that TSV was averaged for each indoor condition. We also noted a very high difference between air and operative temperatures within the data (up to 7 °C difference and 2.6 °C on average). Overall, the assumptions and outcomes of these studies lead us to question the applicability of the human body exergy concept for increasing comfort in spaces that use radiant systems.

6. Conclusions

We performed a literature review to assess if radiant systems provide better, equal or lower thermal comfort than all-air systems. Studies focusing only on radiant systems or only on all-air systems were not included as they did not inform our comparison. This literature review brought five studies that could not establish a thermal comfort preference between all-air and radiant systems and three studies showing a preference for radiant systems. These studies used multiple methods to demonstrate their findings and, in addition, several types of all-air and radiant systems were tested. The two systems performed similarly when compared based on building energy simulation [55], laboratory studies [64,69] and human subject testing in laboratory conditions [76,75]. Radiant cooling ceiling panels showed better results than all-air systems based on laboratory studies [65] and occupant responses in a building [47]. A side-by-side field comparison between an all-air system and TABS with DOAS that was based on occupant survey responses showed increased satisfaction with thermal comfort for the radiant system [77]. All these studies were fully (or mainly) about cooling applications (only one heating variant in Ref. [47]). Overall, we found that a limited number of studies are available and therefore a solid answer cannot be given. Nevertheless, there is suggestive evidence that radiant systems may provide equal or better comfort than all-air systems. Further studies are needed to confirm this statement. Both systems are able to provide acceptable thermal comfort, depending on several factors, including operation and control.

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