Analysis of the energy and thermal performance of a radiant cooling panel system with integrated phase change materials in very hot and humid conditions

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Abstract. This study evaluates the energy and thermal performance of a radiant cooling panel system with integrated phase change materials (PCMs) for application in building retrofit projects. The focus is on the energy saving potential of using two different strategies to avoid condensation in very hot and humid climate conditions. The cooling energy consumption of a DOE medium office prototype building model with a conventional all-air system is used as a baseline for comparing the proposed configurations. The results show that the radiant system yielded energy savings of around 48% compared to the all-air system for existing office buildings. Results also show that the proposed system is able to operate only during the night-time, which improves the plant efficiency. Thus, the energy savings are mainly due to a reduction in the energy consumption of the cold generation system and lower energy use for ventilation compared with conventional air systems.

1. Introduction

Rising average temperatures in cities as a result of global and local climate change in combination with the projected population and economic growth are expected to increase tremendously the future cooling energy demand of buildings and make it the dominant energy component (1). This is already evidenced in the statistics presented by the IEA, which shows that space cooling is the fastest-growing use of energy in buildings, more than tripling between 1990 and 2016 (2). The IEA also estimates that on current trends, energy needs for space cooling will more than triple between 2016 and 2050 (2).

To face the problem of future growth of the global cooling energy demand in buildings and the associated effects on climate change, researchers around the world have focused on improving the efficiency of HVAC systems as well as the thermal-energy performance of the building envelope. This study focuses on the evaluation of an alternative cooling system. The principle of the proposed system is based on the radiative cooling aspect of a known technology such as Thermo Active Building Systems (TABS). TABS are a good solution to improve indoor environmental quality while reducing building energy consumption for heating and cooling (3). However, one downside to the application of TABS is that the system requires massive building structure (thermal mass) for thermal storage, which limits its application to new buildings. In fact, the literature (4,5) shows that research is still required to encourage the application of TABS in existing buildings, which account for the largest share of the total building stock.

As a potential solution, the system proposed in this study considers the use of a radiant cooling panel system with integrated Phase Change Materials (PCM). Although an extensive amount of publications on TABS and PCM can be found (6,7), these two technologies are usually investigated separately. PCMs are not used in common TABS configurations as the building structure (generally concrete slabs) provide the required thermal mass capacity for the system. However, the combination of PCM with TABS could be an important consideration for retrofitting existing buildings, as the required thermal mass capacity could be incorporated in building components containing PCM or in PCM based radiant
heat exchangers, without modifying the building structure. Only a limited number of studies have been found in the literature regarding the integration of TABS and PCM (8,9).

Koschenz and Lehmann (8) developed a thermally activated ceiling panel based on gypsum with microencapsulated paraffin (25% by weight) for its incorporation into lightweight and retrofitted buildings. The system was designed to absorb the thermal loads of office buildings during the daytime and then cooled down by means of the water pipe system. The experimental investigation indicated that the panel was able to store 290 Wh/m² during the 7.5 h of the melting process. Authors determined that a 5cm layer gypsum panel with 25% of PCM by weight was adequate to maintain a comfortable room temperature in glazed façade office buildings. As a drawback, the paper was not elaborated on the necessary energy required to discharge the panels.

Tzivanidis et al. (9) performed a detailed parametric analysis of a TABS with pipes embedded in a PCM layer added to ceiling. The PCM is actively charged with cold during the night at off-peak rates and discharged passively during the day due to internal heat gains of the room. The introduced PCM layer in conjunction with night cooling offered the advantages of low energy consumption, high cool storage capacity, operation under reduced night electricity price, smoothing of electricity consumption by eliminating daily peak loads, improved thermal comfort and elimination of ceiling dripping.

The aim of this paper is to evaluate the energy and thermal performance of a radiant cooling system with integrated phase change materials (PCMs) for application in building retrofit projects. The energy model of a medium office building with the radiant system was developed and evaluated in climate zone 1A conditions, which could be considered as the main challenge for radiant cooling systems. The high humidity ambient air conditions in climate zone 1A requires a more advanced design and control strategy in order to avoid condensation risks (10). Thus, the study will focus on evaluating the energy saving potential of using two strategies to avoid condensation in very hot and humid climate conditions.

2. Methodology
2.1. Description of the building model
A DOE medium office prototype building model compliant to ASHRAE 90.1-2010 for climate zone 1A (very hot-humid) was selected as a baseline for evaluating the energy performance of the radiant cooling system. The model of the office building has three floors with a total floor area of 4980 m². Each floor has four perimeter zones and one core zone, which are all conditioned. The core zones account for 60% of the floor area on each floor. The window-to-wall ratio is 33% with evenly distributed windows along four façades. Floor to ceiling height is 3m.

The climate data for Miami, FL corresponding to US climate zone 1A (very hot and humid) was selected in order to assess system performance under hot-humid conditions. The cooling design day peak dry and wet bulb temperatures are 33.2°C and 25.3°C, respectively. The properties of the building zone and its heat gains are summarized in Table 1. The schedules used in the simulations for occupancy, lighting, and plug and process are predetermined from the DOE prototype building model.

Table 1. Properties of opaque exterior envelope and internal loads of the medium office building. Zone complies with ASHRAE 90.1-2010 requirements for climate zone 1A.

| Exterior opaque envelope properties | Zone loads |
|-----------------------------------|------------|
| Walls: Typical insulated steel framed exterior wall R-8.06 | People 18.58 m² per person |
| Floor: Typical insulated carpeted 6 in. slab floor | Lights 9.6875 W/m² |
| Windows: Single pane windows REF colored 6 mm with shades | Plug and process 8.0729 W/m² |

2.2. Simulation parameters for the radiant cooling system with integrated PCM
2.2.1. Radiant system description (water-loop). The simulated radiant cooling system consists of a piping loop embedded in pure organic PCM and installed in the ceiling of the medium office building.
The piping loop consists of PEX pipes with a diameter of 12.7 mm and a pipe spacing of 154 mm. The ceiling is modeled as an internal source construction, consisting of four layers that include (from outer to inner surface): 100 mm normal-weight concrete; 20 mm of insulation R-27.78; and two PCM layers (15 mm each) in which PEX pipes are embedded. After performing a parametric analysis with different PCM melting temperatures, CrodaTherm 21 with a peak melting temperature of 21°C, a latent heat of 190 KJ/kg, and a thermal conductivity of 0.18 W/m°C (in solid state) was selected for the simulations.

A water-cooled chiller with a reference COP of 5.5 is used for providing chilled water to the radiant system at a constant supply water temperature of 15°C. A new control strategy was developed for this study, which uses the radiant surface temperature and the maximum operative temperature experienced during the day as control variables. Also, considering that night-time pre-cooling has advantages such as operating at more efficient cooling plant conditions, lower electricity energy costs, and reduced electricity demand charges, the radiant system is operated only from 18:00 p.m. to 6:00 a.m. The water-loop of the radiant system is turned on when the radiant surface temperature is higher than 22°C (which should be an indication that the PCM is completely melted) and the maximum operative temperature during the day is above 26°C. The proposed control strategy was implemented using the Energy Management System (EMS) feature in EnergyPlus.

2.2.2. Air-system description (air-loop). In this study, two strategies (cases) have been simulated to avoid condensation risk in high humidity ambient air conditions: conventional case which considers parallel operation of radiant cooling and a dedicated outdoor air system (DOAS) with energy recovery ventilator ERV and; advanced case which considers parallel operation of radiant cooling and a DOAS with ERV and desiccant dehumidification (see Fig. 1).

In both configurations, the DOAS provide the minimum amount of ventilation air required by ASHRAE Standard 62 and the supply air temperature follows the outdoor temperature within the range of 16 – 20°C. When the outdoor temperature exceeds 20°C, the air is cooled using a single speed direct expansion (DX) cooling coil with a gross rated cooling COP of 4. An ERV is also used in both configurations of the air-system to precondition the incoming outdoor ventilation air. The sensible and latent effectiveness of the ERV at 100% cooling air flow is 0.75 and 0.69, respectively. The air system in the two configurations operates from 8:00 to 17:00 and also when the mean air dewpoint temperature is 1 °C below the radiant surface temperature. To implement this control strategy, the EMS feature in EnergyPlus was also used.

For the advanced case, a dehumidification system was modeled by placing a desiccant wheel in series with the DX cooling coil, with the regeneration side of the wheel upstream of the cooling coil and the process side downstream of the cooling coil (see Fig. 1). In this specific configuration of the desiccant wheel, a separate regeneration air stream is not required.

Figure 1. Schematic diagram of the air loop and water loop of the radiant panel cooling system for a) conventional case, and b) advanced case.
2.3. Simulation parameters of the conventional all-air system (baseline case)
The HVAC system of the baseline case is a predetermined all-air system included in the DOE prototype building model, which consists of a packaged air conditioning unit. The model of the system considers three air loops (one for each floor) that include a two-speed DX Cooling Coil 376 kBtu/hr 9.8 EER and a gas heating coil. The zones in each air-loop include VAV terminal boxes with damper and electric reheating coils. The temperature set-point of the conventional all-air system is set to 24°C.

3. Results
The HVAC annual energy consumption breakdown and moisture condensation time for all the considered cases is presented in Table 2. In the evaluated climate, annual energy savings of 48% can be obtained when using a radiant cooling panel system with integrated PCM, compared to a conventional all-air system. Annual energy savings of around 16 MJ/m² are obtained due to reduced fan energy consumption, as the radiant cooling systems have a reduced airflow requirement. The radiant systems require an additional amount of energy for pumping water (around 8.9 MJ/m²), but this is still less than the energy savings due to reduced fan energy consumption. The dehumidification system of the advanced case helps to reduce moisture condensation time in the radiant surfaces from 58 to 12 hrs. during the whole year, while maintaining the same energy use intensity.

Table 2. Breakdown of the annual energy use intensity and moisture condensation times for the evaluated cooling systems.

| Type of system                  | Energy Use Intensity (MJ/m²) | Moisture condensation time (hrs.) |
|--------------------------------|------------------------------|----------------------------------|
|                                | Cooling (water-loop)         | Cooling (air-loop)               | Fans | Pumps | Total |                          |
| Baseline                       | 0                            | 162.26                           | 21.68 | 0     | 183.94 | 0                          |
| Rad. System (conventional case)| 59.81                        | 20.4                             | 6.05  | 8.88  | 95.14  | 58                         |
| Rad. System (advanced case)    | 60.69                        | 20.06                            | 5.49  | 8.88  | 95.12  | 12                         |

Figure 2 shows a comparison of the simulated operative temperature distribution during occupation hours for the baseline case (all-air system) and for the advanced case (radiant system with desiccant dehumidification). Operative temperatures in the range of 22 – 26°C are considered acceptable, as this range corresponds to -0.5 to +0.5 predicted mean vote (PMV) at an airspeed of 0.15 m/s, occupant metabolic rate of 1.2 met and variations in relative humidity (between 40 to 60%) and clothing insulation (0.5 to 0.7 clo). As can be seen in Figure 2, the radiant system (advanced case) is able to maintain indoor thermal comfort conditions in most of the building zones for at least 80% of the occupation hours. The perimeter zone (west side) could be considered as the critical zone, as operative temperatures are lower than 22°C for about 18% of the occupied hours, and higher than 26°C for about 6% of the occupied hours. However, the lower temperatures normally occur during the first and last months of the year, which are not cooling dominant periods and heating is not provided. Based on the results, it can be concluded that the proposed radiant cooling panel system with integrated PCM is able to maintain similar indoor thermal comfort conditions than a conventional all-air system.

Figure 2. Simulated operative temperature distribution during occupation hours.
The following results are focused on analysing the performance of the simulated systems in the most critical zone of the office building (west-facing perimeter zone of the top floor). Figure 3 shows 24-hour heat transfer rate profiles for the radiant cooling panel system with integrated PCM (advanced case) and for the all-air system (baseline), during the summer design day (July 21st). The peak heat removal achieved by the all-air system is 95 W/m². In the case of the radiant cooling system with integrated PCM, the peak heat removal of the ventilation system is 3 W/m², the peak heat removal of the active PCM-ceiling is 40 W/m², and the peak hydronic cooling load is 92 W/m².

![Figure 3. Heat transfer rate of the simulated systems during the summer design day (July 21st).](image)

In Figure 4, 24-hour profiles of the operative temperature and the ceiling surface temperature of the two simulated systems are shown for the summer design day (July 21st). In the case of the radiant cooling system with PCM, the radiant ceiling surface containing PCM is at around 20°C at 6:00 am, which should be an indication that the PCM is in solid state after circulating chilled water during the night-time (from 18:00 to 06:00). From 06:00 to 18:00, the PCM-ceiling surface is able to passively remove heat gains from the interior zone until it reaches a temperature of around 22°C, which should be an indication that the PCM is in liquid state. The indoor mean air dewpoint temperature is also presented for the radiant cooling system with PCM, in order to show how the ventilation system is able to maintain the dewpoint temperature below the radiant surface temperature to avoid moisture condensation risks. As expected, the all-air system is able to reduce zone operative temperature fluctuations, but as previously discussed, both systems offer similar thermal comfort conditions.

![Figure 4. Operative temperature and ceiling surface temperature of the two simulated systems during the summer design day (July 21st).](image)

4. Discussion of results and Conclusions

Overall, the results indicate that the evaluated radiant cooling system with integrated PCM can be used in building retrofit projects to provide adequate indoor thermal comfort conditions, as it showed a similar thermal performance than all-air systems while operating at temperatures considered adequate for high temperature cooling.

Annual energy savings of 48% can be obtained in a very hot and humid climate when using a radiant cooling panel system with integrated PCM, compared to a conventional all-air system. The energy savings are mainly due to a reduction in the energy consumption of the cold generation system and lower energy use for ventilation, as the maximum airflow rate of the radiant system with PCM is considerably
lower than that of the all-air system. However, to determine if the radiant cooling system with PCM could be considered an energy saving measure for building retrofit projects, future work will focus in evaluating its performance under different climates, occupant loads, and building characteristics.

The implemented strategies for avoiding moisture condensation risks in very hot and humid climates could be considered successful, as the advanced case of the radiant system with PCM showed only 12 hrs. of moisture condensation time during the whole year, while maintaining the same energy use intensity of the conventional case (without desiccant dehumidification). By having a PCM melting temperature of 21°C, the radiant surface temperature was maintained at a minimum of 20°C which also helped to avoid moisture condensation risks.

The results of the study also showed that the evaluated radiant system with integrated PCM is able to maintain a comfortable indoor temperature for at least 80% of the occupied hours while operating only during night-time. The simulated operative temperature distribution during occupation hours indicate that cold temperatures (20 - 22°C) are the main cause of thermal discomfort conditions in the evaluated building zone. However, this result is expected as the system was evaluated during the whole year, which includes months that have a mixed cooling and heating demand and no active heating was provided.

The heat transfer rates of the simulated systems during the summer design day showed that the radiant cooling system with PCM was able to shift most of the cooling load to the night-time, which helped to operate the chiller at more efficient conditions (higher COP). Night-time operation will also have additional advantages such as lower electricity energy costs, reduced electricity demand charges and increasing the possibility of using low-grade energy sources, which will be evaluated in a future work.

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