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Authors

Bauman, Fred
Raftery, Paul
Karmann, Caroline

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Lessons learned from field monitoring of two radiant slab office buildings in California

Fred Bauman[a,1], Paul Raftery[a], Caroline Karmann[a]

[a]Center for the Built Environment, 390 Wurster Hall, University of California, Berkeley, CA 94720-1839, USA

Abstract

In this paper we present the results from field studies of two low-energy office buildings in California, both using radiant slab ceiling systems (thermally activated building systems, TABS) for primary cooling and heating in the buildings. Both buildings are certified LEED Platinum and incorporate a wide range of energy efficient technologies and design strategies, including TABS, advanced shading systems, underfloor air distribution, chilled beams, ceiling fans, natural ventilation, and photovoltaic panels. Findings and analysis from the following building performance assessment techniques will be discussed.

- Occupant satisfaction survey. Occupant surveys are an invaluable source of information for describing how well the building is providing a high quality indoor environment for the occupants. In addition, the survey results are also compared against a large benchmark survey database of over 50,000 occupants.
- Wireless measurement system. A network of wireless sensors was installed in selected zones of the buildings to provide additional more detailed information about the operation and control of the radiant slab system. This data was combined with trend data from the building management system (BMS) to examine the performance of the buildings during both winter and summer conditions. Some control issues were identified and corrected based on these measurements.
- Energy performance analysis. We collected utility data for 2014 in one of the buildings and used this information to determine the building's Energy Star rating.

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Keywords: Thermally activated building systems; radiant slab systems, whole-building technologies, energy efficiency, occupant survey, field monitoring; controls.

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[1] * Corresponding author. Tel.: +1-510-642-7848; fax: +1-510-643-5571.*E-mail address:* fbauman@berkeley.edu

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1. Introduction

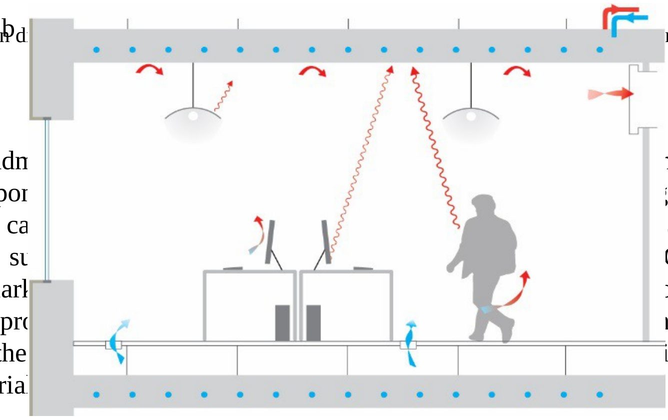
Radiant cooling and heating systems provide an opportunity to achieve significant energy savings, peak demand reduction, load shifting, and thermal comfort improvements compared to conventional all-air systems. As a result, application of these systems has increased in recent years, particularly in zero-net-energy (ZNE) and other advanced high performance buildings. An online map is now available based on a database of representative buildings with radiant systems here: http://bit.ly/RadiantBuildingsCBE. A status report by New Buildings Institute (NBI) on 160 ZNE commercial buildings in North America shows a trend away from forced-air heating, ventilation, and air-conditioning (HVAC) systems and increased adoption of radiant systems by these exemplary buildings [1]. A recent article reported on a large side-by-side comparison between an optimized variable-air-volume (VAV) system and a radiant slab system with a dedicated outdoor air system (DOAS) [2]. The 23,200 m^2 building, located in hot and humid Hyderabad, India - a very challenging climate for radiant systems - was divided into two identical halves. Each half was conditioned by just one of the systems so that a fair comparison could be made. After the first two years of operation, it is reported that the radiant system has used 34% less energy compared to the VAV system and the results of an occupant satisfaction survey also indicate greater satisfaction with thermal comfort for the radiant half of the building (63% satisfaction rate for radiant vs. 45% satisfaction rate for VAV system).

Other studies aimed to identify energy saving design features enabling new medium or large office buildings to achieve 50% energy savings compared to a building just complying with ASHRAE Standard 90.1-2004 [3]. These studies identified hydronic radiant systems with DOAS as one of the leading energy saving strategies. This combination was predicted to achieve 56.1% energy savings (national weighted average) for 16 different climate settings, with an average payback of 7.6 years [4,5].

Despite growing interest in radiant systems, information about how best to design and operate them is limited, as is specific information about occupant satisfaction in these buildings. This lack of information hinders their wider acceptance in the generally-conservative building industry. The purpose of this research was to conduct two detailed case studies in high performance buildings, both using radiant slab ceiling systems (thermally activated building systems, TABS). The two buildings are the David Brower Center in Berkeley, CA, and the Sacramento Municipal Utility District (SMUD) East Campus Operations Center in Sacramento, CA. By providing enhanced knowledge about successful radiantly conditioned buildings we hope to encourage further adoption of this space conditioning technology, facilitating the production of zero-net energy buildings.

2. David Brower Center, Berkeley, California

The David Brower Center (DBC) is a 4-story 4,200-m^2 LEED Platinum office building located in downtown Berkeley, California (Fig. 1a). The building was completed and first occupied in May 2009. It contains lobby and public meeting space on the first floor and open plan office spaces on the 2nd-4th floors. The goal of a low energy building was achieved through an integrated design process that combined thermal mass, shading, and insulation into an efficient building envelope, implemented daylighting and efficient lighting control strategies, and used a low energy HVAC system. The primary space conditioning subsystem is hydronic in-slab radiant cooling and heating, often referred to as thermally activated building system (TABS), which is installed in the exposed ceiling slab of the 2nd – 4th floors of the building. Due to their larger surface area and high thermal mass, TABS use relatively warmer chilled water temperatures, making them well-matched with non-compressor-based cooling, such as cooling towers. In addition to the improved efficiency of transporting thermal energy with water vs. air, the building cooling energy savings are attained through the utilization of a cooling tower, instead of a chiller, to make cooling supply water. Ventilation air is provided by an underfloor air distribution system (Fig. 1b). The design, performance, and lessons learned have been described by Rumsey and Weale [6].



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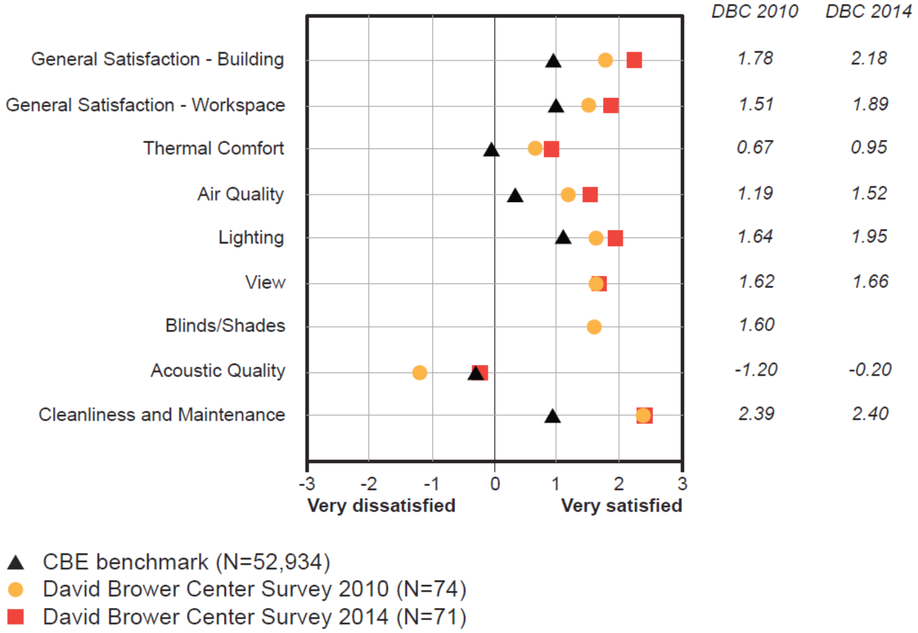

Fig. 2. Average occupant satisfaction ratings for indoor environmental quality by category for DBC surveys from 2014 and 2010 in comparison to CBE benchmark database from 2010.

1.2. Energy performance

The Energy Star rating system was developed to evaluate the energy performance of an individual building by comparing it to a large database for similar buildings in the U.S. [8]. Table 1 shows the Energy Star rating for DBC during 2014 based on the annual electricity and gas bill, including photovoltaic production. By achieving a rating of 99, the same as that obtained in 2009-2010, DBC demonstrates an energy use intensity that is lower than 99% of other similar (mid-size office) buildings.

Table 1. Energy Star performance results: David Brower Center.

Performance metric	2009-2010	2014	National median (2014)
Energy Star Rating	99	99	50
Site energy use intensity (GJ/m^2)	0.53	0.52	1.54
Source energy use intensity (GJ/m^2)	0.77	0.80	2.37

3. SMUD East Campus Operations Center, Sacramento, California

The SMUD East Campus Operations Center is a 18,600-m^2 LEED Platinum certified office building (Fig. 3) that includes a great number of energy efficient technologies and design strategies: TABS, radiant embedded surface ceiling system, chilled beams, geothermal exchange, thermal energy storage tanks, heat recovery wheel, ceiling fans, high thermal mass, advanced window blinds that redirect solar energy onto ceiling, etc. Radiant ceiling slabs (TABS) are used in all open plan offices, the embedded surface ceiling system serves a few perimeter zones, and active chilled beams are used in separate interior zones (e.g., meeting rooms) with variable loads. The site also integrates a large area of solar photovoltaic panels that enable the whole campus (five buildings in total) to approach ZNE.

Fig. 3. Sacramento Municipal Utility District (SMUD) East Campus Operations Center, Sacramento, CA.

The SMUD building was completed and occupied during the summer of 2013. An occupant satisfaction survey was completed in December 2014, however we are still awaiting final analysis of the results. The overall energy performance of the building is quite complex due to the multiple sub-systems, and to date, detailed energy use data are not available. The research team installed approximately 50 wireless sensors in the open plan office area of the south zone on the 2nd level of the building in December 2013. We have also been collecting and analyzing trend data from the building management system (BMS).

1.3. Trend data analysis

Fig. 4 shows zone air temperature, slab surface temperature, and radiant slab water valve position for the southeast perimeter zone during December 2013 when the research team first started monitoring the building. The weather at the time was clear and cool. The air temperature of the zone rises above 24°C each day around 10:00-12:00, and at this time the water valve opens and the slab is cooled down until 16:00. This control strategy is more representative of how a quick-response all-air system is controlled. A preferred approach would be to adjust the controls so that the slab is precooled in the early morning, thereby avoiding active cooling during the middle of the day and shifting system cooling loads to more efficient and cost-effective nighttime hours, as shown in Fig. 5.

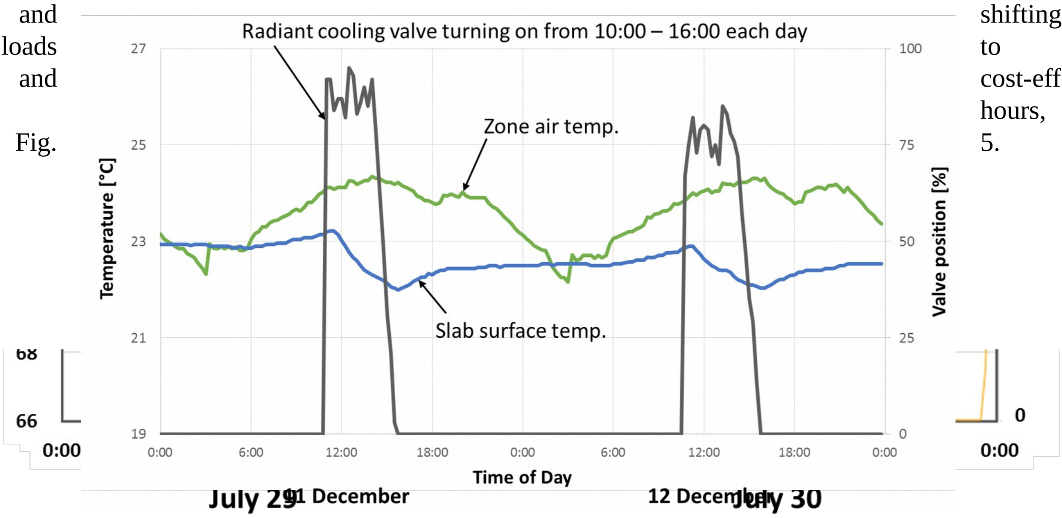

Fig. 4. Radiant system control in southeast zone, 2nd level of SMUD building: December 2013

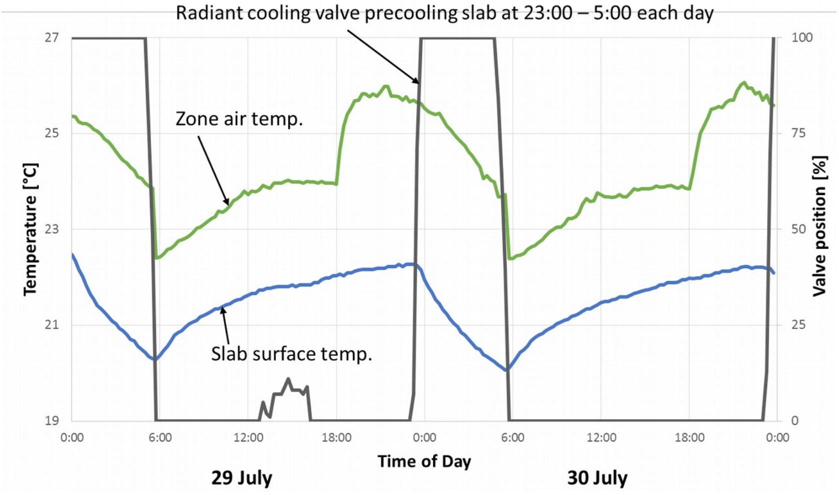

Fig. 5. Radiant system control in southeast zone, 2^{nd} level of SMUD building: July 2014.

Fig. 5 presents results from the same southeast zone during the following summer in 2014 when peak outside air temperatures exceeded 38°C for four consecutive days beginning on July 29. By this time, building operators had made control changes to enable the radiant slab to be precooled from 23:00-5:00 each night, thereby allowing active cooling of the slab to be minimized during the following afternoon, demonstrating a very effective operation of the building during hot weather.

It was discovered that perimeter zone thermostats, embedded in the exterior wall, were unsealed and exposed to airflow in the wall cavity. Airflow from the building into the wall cavity was dependent on a slight positive pressure maintained by the air handling unit (AHU). When the AHU was turned off at night, the thermostat temperature dropped as the thermostat was now reading the much cooler air coming from the cavity. However, when the AHU started up at 5:00 in the morning, and the building was pressurized again, the thermostat increased by about 3°C (see Fig. 6). After the thermostats were sealed and insulated on 4 April, this large shift was eliminated. It is important to ensure that thermostats used for radiant system control are representative of zone temperatures, regardless of whether the air system is turned on or off as radiant slab systems often operate at night when air systems are off.

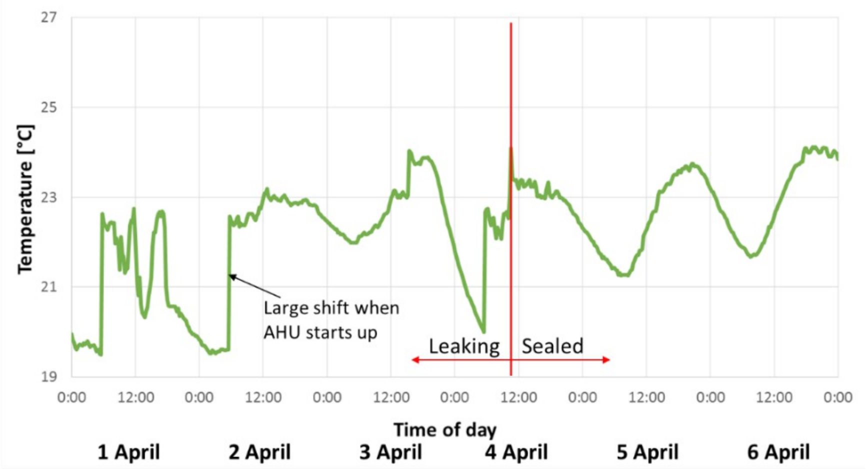

Fig. 6. Sealing of thermostat on 4 April eliminates large shift in thermostat temperature upon AHU start-up.

4. Conclusions

Two case studies of radiant slab systems are reported. The David Brower Center demonstrated exceptional energy performance and occupant satisfaction with indoor environmental quality. The SMUD operations center provided valuable lessons learned about controlling the radiant slab system. The building was able to successfully maintain comfortable zone temperatures during hot summer days by precooling the radiant slab during the night. For more details of both case studies, please refer to the final research report [9].

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