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Analysis of a hybrid UFAD and radiant hydronic slab HVAC system.

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Abstract

In this paper, an EnergyPlus simulation model was used to simulate the operation of a novel integrated HVAC system. This system combines an underfloor air distribution system with a cooled radiant ceiling slab. A cooling tower supplies water to pre-cool the structural slabs during the night and early morning period. The paper compares the performance of this system to both an overhead system and an underfloor air distribution system in the cooling season for the Sacramento, California climate. The UFAD/Radiant hybrid system shows an energy reduction of between 21-25% during the peak cooling months, an electricity demand reduction of 27% during the peak hour, and improved occupant thermal comfort.

Keywords: underfloor air distribution; radiant cooling; energy performance; thermal comfort; EnergyPlus.

1. Introduction

Underfloor air distribution (UFAD) systems use open spaces (plenums) between structural concrete slabs and a raised access floor system to supply conditioned air directly to the occupied zone [1]. Appropriately designed UFAD systems have several potential advantages over traditional overhead systems, such as improved thermal comfort, indoor air quality (IAQ) and energy efficiency as well as reduced life cycle costs, particularly in buildings with high churn rates. UFAD systems are widely used globally in a variety of configurations [2]. UFAD technology has been thoroughly investigated through case study investigations, full-scale testing and bench scale laboratory testing, computational fluid dynamic simulation and whole building simulation [3-7].

Radiant hydronic cooling systems rely on pipes to distribute cooled water throughout a building, as opposed to a conventional all-air system, which uses chilled air and ductwork. These radiant systems are commonly implemented as hydronic (polytetrafluoroethylene, or PTFE) tubing embedded in a concrete slab. Such systems, often known as thermally activated building systems (TABS), use the thermal inertia of the slab to reduce peak loads and to allow for pre-cooling strategies. These strategies involve cooling the slab during the night and morning periods when outdoor temperatures are low. The thermal inertia of the cooler slab then reduces zone loads throughout the day. Radiant hydronic systems have a number of advantages over traditional air systems, such as improved thermal comfort due to lower radiant temperatures. In addition, they are generally more energy efficient because of smaller operating temperature differentials and lower transport energy consumption. These systems have been in use for decades, and have been thoroughly investigated through case studies, full-scale testing, laboratory testing and whole building simulation [8-12].

Lately, with growing concern about preserving the environment and efforts to achieve significant reductions in building energy use, there has been increasing interest in advanced integrated systems (a combination of two or more low-energy building systems) within the building industry. The driving factor behind the work in this paper was to investigate the performance of a novel integrated HVAC system that combines a UFAD system with a

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radiant hydronic slab. Specifically, this paper illustrates the potential for summer energy savings using this HVAC system served by a free-cooling tower to pre-cool the building during the night and early morning periods. This hybrid system should benefit from improved thermal comfort, improved indoor air quality, lower energy consumption, and an improved electrical demand profile when compared to the standalone systems. In addition, the UFAD/Radiant system could mitigate some of the operating difficulties or disadvantages of the standalone systems, such as reducing thermal decay (temperature gain) issues in underfloor supply plenums, and tighter indoor temperature ranges than are typical of TABS due to the slow response associated with these systems. Several existing buildings use a hybrid of both UFAD and hydronic slab systems, such as the David Brower Center, Berkeley, CA USA [13] and the TiFS Engineering Headquarters, Padua, Italy [14].

2. Methods

2.1. UFAD/Radiant model description

The UFAD/Radiant system (Figure 1) was modeled using EnergyPlus v3.1 [15]. The model uses three thermal zones, or layers (below) – one for the supply plenum, one for the occupied lower sub-zone, and one for the upper sub-zone. The supply plenums are in series (i.e., the diffusers are not ducted) and thus supply air passes through the interior supply plenum zone before entering the interior occupied lower sub-zone and the perimeter zone supply plenums. The model calculates the thermal decay of the supply air as it passes through the supply plenum (i.e., temperature rise due to heat gain from the floor slab and raised floor panels). The UFAD model is based on a typical underfloor air distribution system that uses pulse-modulated airflow boxes for interior zones and fan-assisted reheat boxes with water-fin-tube coils for perimeter heating. The model represents these using Variable Air Volume (VAV) dampers for interior zones and a combination of unit heaters and VAV dampers with reheat (RH) coils for perimeter zones. These systems maintain temperatures between 21.1°C and 23.9°C in all the occupied lower sub-zones (T_{stat}).

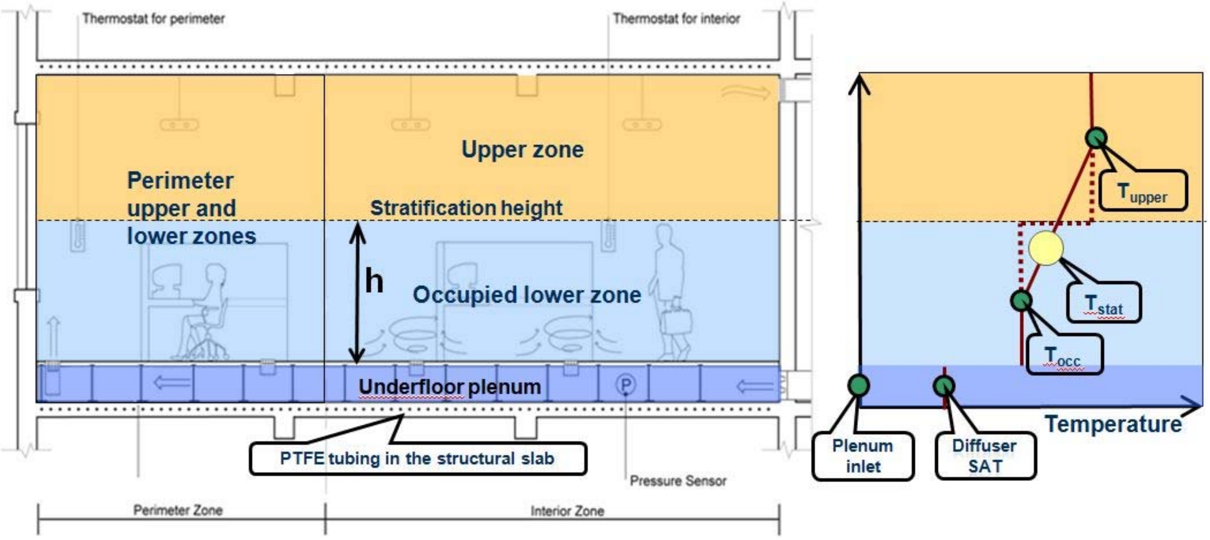

Figure 1 Cross-section of typical interior and perimeter zones on middle floor of building

Radiant hydronic tubing at the center of the 150 mm thick ceiling slabs pre-cools the building during the night and early morning. New slab control features were added to EnergyPlus v3.1 for the purpose of this analysis. The new control algorithms vary the slab flow rate to meet a set-point temperature measured either at the center, or at the ceiling surface (i.e., bottom), of the slab. Essential modifications were also made to allow the radiant hydronic slab system to operate when the zone thermostat (T_{stat}) temperature is below its cooling set-point temperature, even if the UFAD system is also operating. The hydronic slab systems in perimeter zones do not operate during the swing season months (May and October) as the increased reheat and pump/tower energy consumption exceed the savings in cooling energy.

An Air Handling Unit (AHU) supplies air to the building using variable speed supply and relief fans. The AHU maintains a fixed supply air temperature using an airside economizer (a mixing box) and heating and cooling coils. A water-cooled chiller supplies chilled water to the AHU cooling coils. A two-speed cooling tower combined with a plate heat exchanger operates in 'free-cooling' mode to supply cool water to the slab during night-time and early morning hours while outdoor wet-bulb temperatures are low (Figure 2). Although the real system would operate just one tower, these were implemented in the model as two separate towers due to modeling issues. As these two tower objects do not operate simultaneously and are identical sizes, the simulation closely models the real system. Two identical, staged, forced-draft gas boilers supply hot water (HW) to the AHU heating coil and the reheat coils in each zone. Variable speed pumps supply each water loop.

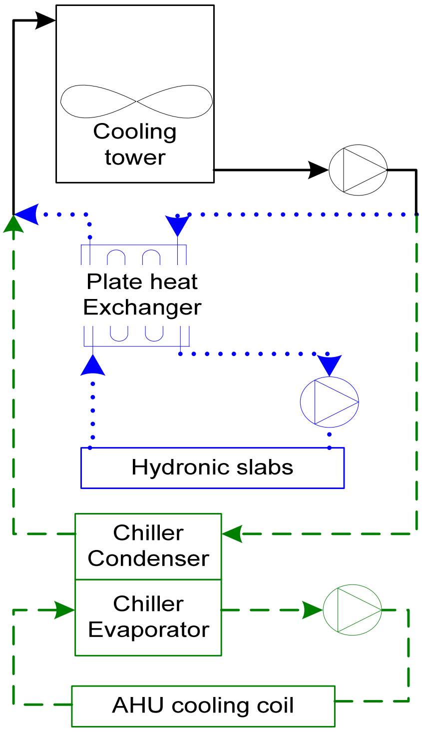

Figure 2: Chilled water plant schematic. Green (dashed) signifies day operation and blue (dotted) signifies night operation

2.2. Comparison models and common parameters

The EnergyPlus v3.1 model discussed above was implemented as an added capability to an existing interface and models used for comparing the performance of two HVAC systems: a good practice variable-air-volume (VAV) overhead (OH) system and a good practice UFAD system. Researchers at the Center for the Built Environment (CBE) at University of California Berkeley have developed this interface and studied it in detail over the course of several years. During this time, numerous modifications to EnergyPlus were made to improve modeling accuracy, including the implementation of the current UFAD module based on experimental correlations [3]. This paper compares the performance of the UFAD/Radiant model to these two models.

The model is of a 3-storey office building with four perimeter spaces, one interior space and one interior service space per floor. Where possible, all model parameters such as those related to geometry, constructions, internal loads, temperature set-points, etc., remain identical in each of the three models in order to obtain fair performance comparisons and isolate the impact of the HVAC system alternatives. Figure 3 outlines the major model parameters. Although each wall in the model consists of multiple layers of individual materials, for the sake of brevity the table represents thermal properties by overall U-value. The solar heat gain coefficient of the windows is 0.3, typical of modern low-e windows. The table also describes the various HVAC capabilities that

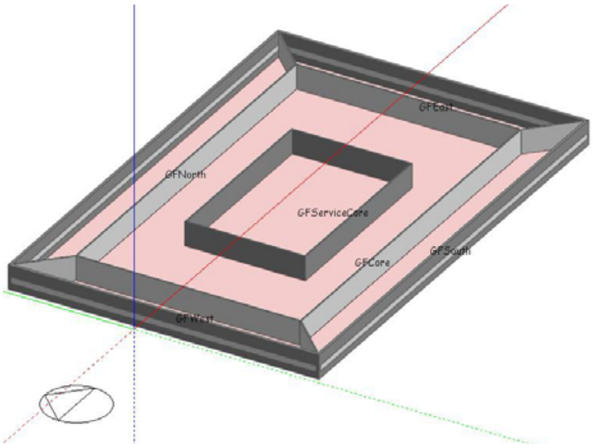

Figure 3: Overview of the floor plate of the model, illustrating the thermal zones on each floor.

Table 1: General model parameters

General building geometry characteristics

Building orientation	Floor area	Perimeter zone depth	Aspect ratio	Window to wall ratio	Shading devices	Ceiling height
0 °	5574 m^2	5 m	1.5	0.4	None	2.74m

Construction U-values (excluding air film resistance)

Exterior wall	Ceiling slab	Roof	Windows	Raised floor[a]	Suspended ceiling[b]
1.27 W/m^2K	2.37 W/m^2K	0.31 W/m^2K	1.65 W/m^2K	3.54 W/m^2K	4.48 W/m^2K

HVAC system and plant parameters

Static pressure reset	Supply air temperature	Global sizing factor	Chilled water temperature reset	Hot water temperature reset	Terminal unit min airflow fraction
Yes	15.55°C, No reset	20%	None	None	Minimum ventilation air

HVAC system and plant curve sources

Equipment	Source
Chiller curves	DOE-2 Centrifugal/5.50COP [16]
Boiler part load curve	CBE estimate based on DOE-2 forced draft curves
Fan and pump part load curves	Courtesy of Taylor Engineering, Alameda, CA, USA

Internal loads

	Lighting loads	Plug loads	Occupancy	Activity level
Value	10.8 W/m^2	8.6 W/m^2	25.5 m^2/ person	139 W/person
Radiant fraction	0.32	0.4	0.6	N/A

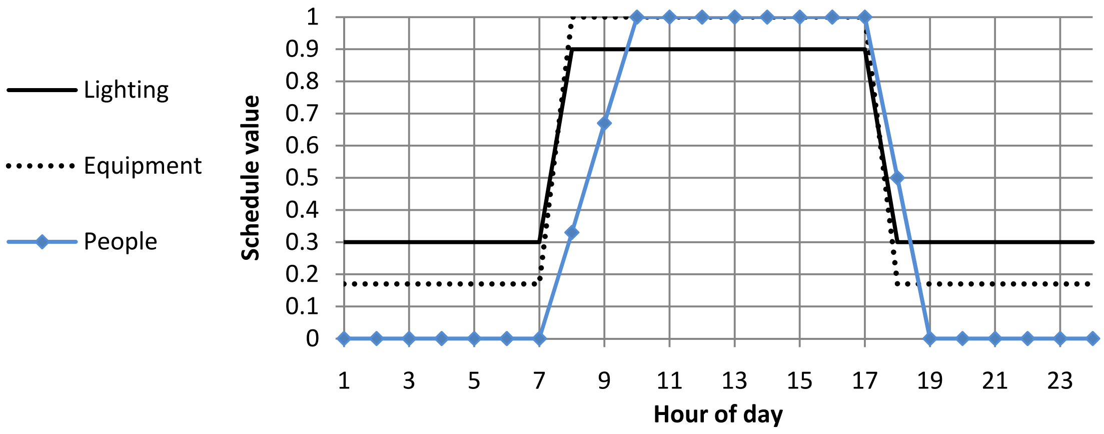

Figure 4: Internal load weekday schedule values

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[a] This construction does not appear in the overhead (OH) simulation.

[b] This construction does not appear in the UFAD simulations without a return plenum.

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remain fixed between all runs, and illustrates the sources of the curves used for all of the HVAC equipment and plant. The model uses internal load densities and schedules derived from DOE-2 prototype models [17] (Table 1 and Figure 4) and minimum ventilation air requirements of 0.76 liters/m^2.s, according to Title 24 of the California Code of Regulations [18].

2.3. Parameters which vary between models

Table 2 illustrates the parameters that vary between models. The overhead (OH) and UFAD runs represent good practice buildings and are used as a baseline for comparison with the UFAD/Radiant runs.

Table 2: Run parameters

Simulation run number	1	2	3
System	Baseline overhead system	Baseline UFAD system	UFAD Radiant baseline
Return plenum	Yes	Yes	No
Supply plenum	No	Yes	Yes
Floor to floor height	3.96 m	3.96 m	3.15 m
Slab operation strategy	-	-	Pre-cool
AHU design static pressure	4.5	3	3

3. Results and discussion

3.1. UFAD/Radiant zone conditions:

Figure 5 illustrates the indoor conditions within a typical zone for the UFAD/Radiant system. A cooling tower supplies cooled water to the hydronic slab system during the night and early morning period when outdoor wetbulb temperatures are low and the chiller does not operate. The newly implemented control method operates the hydronic system to cool each slab until the bottom surface temperature reaches a minimum set-point temperature, in this case 20.5°C. The slab then absorbs heat and gradually warms throughout the day, reducing cooling loads on the air system.

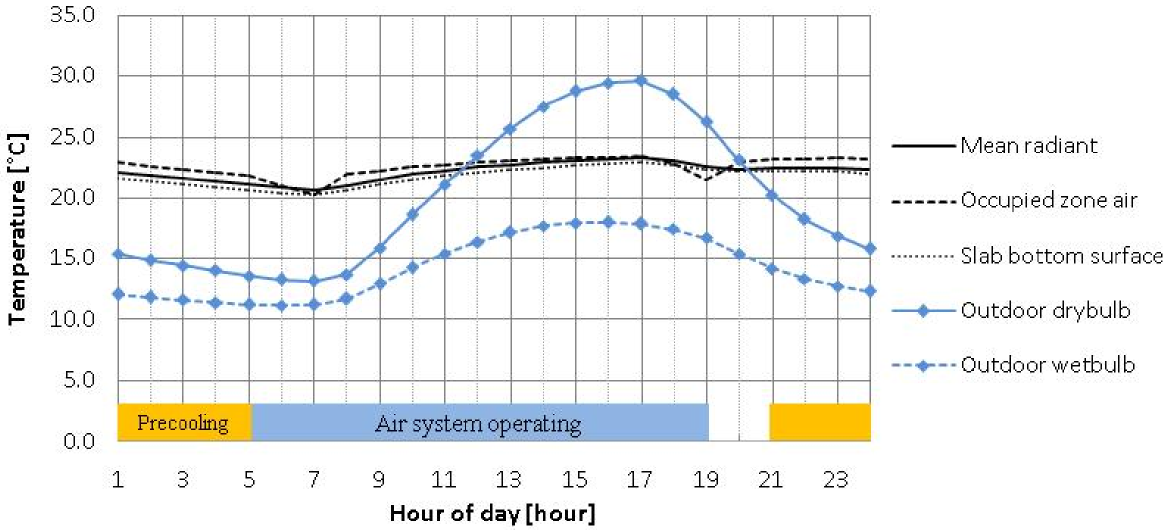

Figure 5: Average July/August midweek temperatures for the UFAD/Radiant middle floor interior zone (run 3).

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3.2. Energy performance comparison

The UFAD/Radiant system performs well when compared to more typical systems. Figure 6 compares the summer energy performance of the baseline systems described in Table 2 above. The 'Aux' category includes all pump and cooling tower energy consumption. The UFAD/Radiant case shows HVAC savings of (21 - 25%) during the peak cooling months from June to August. The majority of these savings are due to reductions in cooling load during chiller operating hours and reduced fan consumption, which are partially offset by increased auxiliary consumption and added perimeter reheat energy. The energy reductions during the swing months are more modest because much of the savings from the pre-cooling strategy are offset by increased reheat energy consumption during the morning warm-up period.

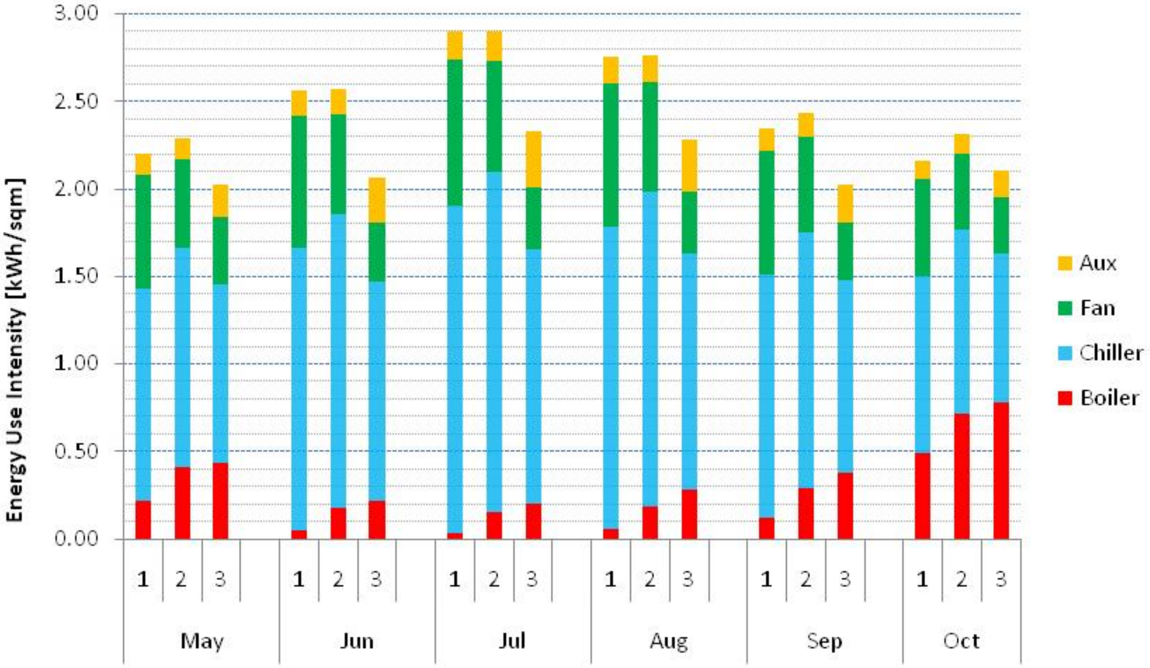

Figure 6: Cooling season HVAC energy consumption for each of the runs described in Table 2.

3.3. Thermal comfort

As Figure 7 illustrates, the UFAD/Radiant system maintains lower occupied zone temperatures and mean radiant temperatures than the UFAD baseline case. This yields improved thermal comfort throughout the majority of the day during the summer months (excluding the very early morning period for the interior zone). Alternatively, the UFAD/Radiant system could demonstrate further energy reductions while maintaining similar thermal comfort levels by using a higher thermostat set-point than the other cases. However, this was not investigated in this research. In addition, the UFAD/Radiant case maintains comfort conditions in interior zones even outside normal office hours, which may be an advantage for buildings that are sporadically occupied during these periods. Figure 7 also shows that the average occupied zone air temperature is always below the cooling set-point for the interior zone (top left) in the UFAD/Radiant case. Thus, for this zone, minimum ventilation air maintains the indoor air temperatures within the comfort range.

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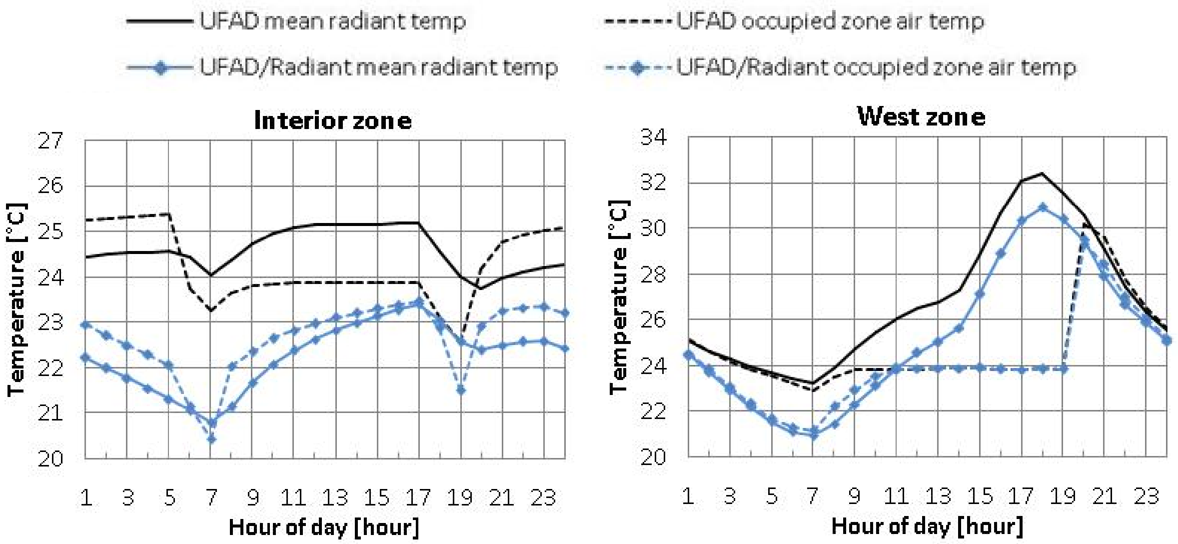

Figure 7: Average July/August midweek mean radiant and occupied zone air temperatures for both the UFAD (run 2) and UFAD/Radiant (run 3) baseline systems for the middle floor interior and west zones.

3.4. Demand reduction

Aside from the monthly HVAC energy saving potential of the UFAD/Radiant system (Figure 6), the time when electricity is used also changes. The precooling strategy shifts a portion of electricity use to the morning and night periods. Figure 8 illustrates that the UFAD/Radiant system improves the demand profile and reduces HVAC electricity consumption by 27% at peak demand (3pm) based on the time-dependent demand data for Sacramento [19].

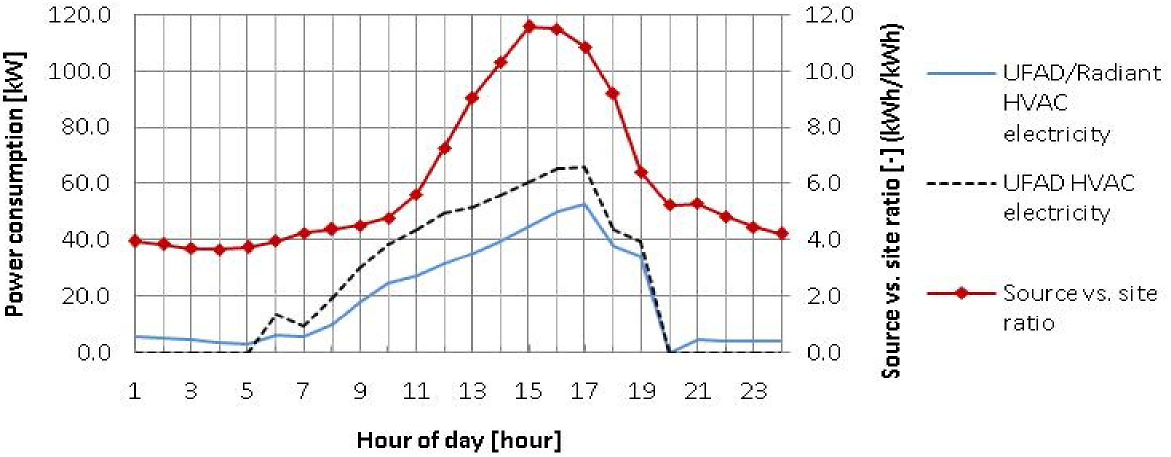

Figure 8: Average July midweek HVAC electricity consumption for both UFAD/Radiant (run 3) and UFAD (run 2) with time-dependent source energy versus site energy ratio for Sacramento in red on the secondary axis.

3.5. Thermal decay

The lower slab temperatures provided by the UFAD/Radiant precooling strategy partially mitigate the issue of thermal decay (i.e., the temperature increase between the air leaving the air handler and the air reaching the diffuser). However, the effect is not very significant because the supply air temperature is much lower than the slab pre-cooling set-point. Figure 9 illustrates this effect by comparing the air temperatures at the interior and east diffusers for both the UFAD/Radiant and UFAD cases. Although there is not a significant reduction in thermal decay, the convective heat transfer from the slab into the supply air decreases 45% and 18% in the interior and east zones respectively (averaged over the period in the graph above), when compared to the UFAD case. This is due to reduced airflow rates, rather than reduced air temperatures. The improvement decreases throughout the day, and the pre-cooled

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slab is less effective for zones that experience higher loads, particularly when those loads occur later in the day, such as the south and west perimeter zones.

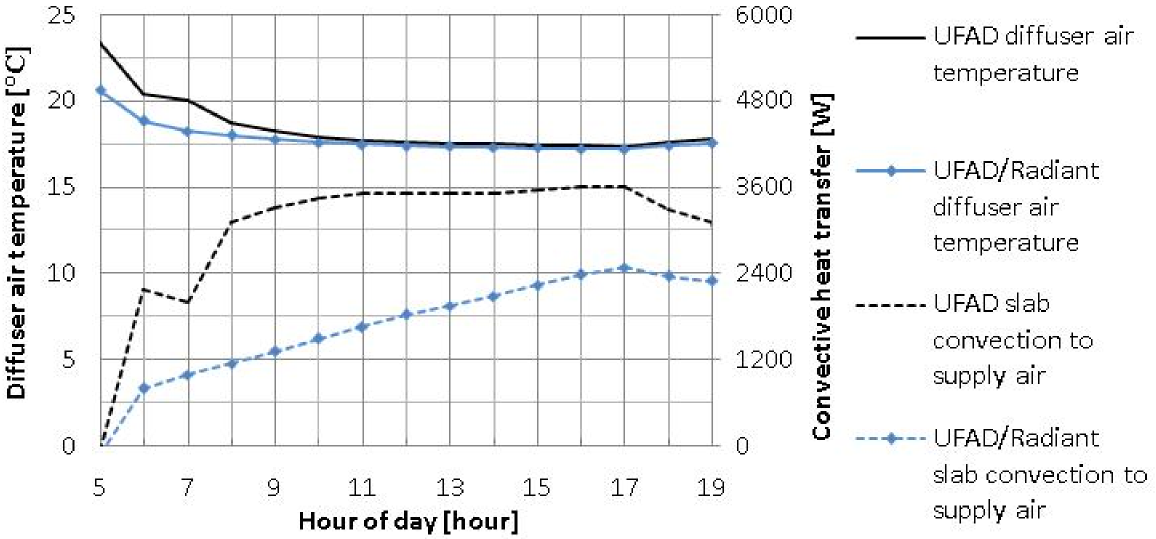

Figure 9: Air temperature reaching the diffuser and convective heat transfer rate between the slab and the supply air for interior zone for both the UFAD (run 2) and UFAD/Radiant (run 3) cases.

3.6. Further discussion

A large number of discrete and continuous parameters affect the results of these simulations and it is not feasible to examine them all in detail. However, over the course of this investigation several significant parameters were noted. For example, supply air temperature (SAT) is a significant variable; lower SATs yield lower energy consumption for all runs. Also, the removal of a return plenum for the UFAD system has a negative effect (1-3% increase in energy consumption during the summer months). However, the reduction in floor-to-floor height (to maintain a standard 2.7m ceiling height) has the opposite effect, and these two effects approximately cancel each other out. In other words, a UFAD system with no return plenum and a reduced floor to floor height has very similar energy consumption to a standard UFAD system.

The UFAD/Radiant system performs better for interior zones than for perimeter zones because these zones are exposed to the exterior and the slabs can be pre-cooled less before the zone air temperature drops below the heating set-point. This increases the amount of reheat energy needed to meet set-point conditions in the early morning ‘warm-up’ period. In addition, the perimeter zone cooling loads are much higher than the interior zones. As the slab has a finite cooling capacity, it is less effective at cooling these zones throughout the entire day. Thus, this system is most applicable to deep plan buildings with large interior zones relative to the perimeter.

There are significant disadvantages to the UFAD/Radiant system. For example, although the chiller and air system are smaller for the UFAD/Radiant case when compared to the UFAD only case (19% and 23% smaller respectively), the added cost of the hydronic tubing and heat exchanger will most likely overwhelm these cost reductions. Also, the added operational (and design) complexity of such a system cannot be overlooked.

It should be noted that several simulation engine limitations may negatively affect the performance of the UFAD/Radiant system proportionately more than the other systems. For example, the current selection of curve types does not allow for accurate representation of boiler consumption at low part load. Furthermore, boiler performance that is dependent on return temperature cannot be simulated in the current model. This precludes the investigation of using a condensing boiler as a low temperature heating system for winter operation of the UFAD/Radiant case. In addition, condenser water pumps in the simulation model are constant speed, and the cooling tower supply water temperature set-point must be fixed instead of maintaining a differential temperature above outdoor wet-bulb temperature. One other caveat is that the current model uses an approximation for ground temperatures under the building (2°C lower than average monthly air temperature of the zone immediately above the ground [16]). This approximation was developed using calculations for standard overhead systems and does not apply as well to underfloor air distribution systems. This difference causes the majority of the additional summer heating consumption seen when comparing run 1 to runs 2 or 3 in Figure 6.

4. Conclusions

A simulation model of a novel HVAC system was created and compared to typical HVAC systems. The UFAD/Radiant pre-cooling strategy shows a HVAC energy consumption reduction of 21- 25% in the summer season in the Sacramento, California climate. This system also reduces average July peak demand by 27% when compared with UFAD, and shows an improved demand profile throughout the day. Furthermore, the UFAD/Radiant case shows improved thermal comfort when compared to more typical systems. However, although cost considerations have not been studied, it appears that these improvements may not offset the additional initial cost of such a system in today’s economic climate; further developments of this system are under investigation.

5. Future work

Future work will focus on investigating a fully integrated system over a 12-month period. This system will include a low temperature heating system (a condensing boiler) which will take advantage of large acting surface areas to allow lower hot water temperatures and thus improve efficiency. This system will also include a cooling system that can supply cool water to the slab throughout the day, as well as using ‘free-cooling’ to precool the slab during the night (which was investigated in this paper). A chiller operating at low lift temperatures with an integrated water economizer is an example of such a system.

Further work will also focus on improvements to the control method; specifically, a means of controlling the starting time of the slab based on a 12 or 24 hour outdoor temperature average.

Laboratory-scale stratification studies for chilled ceiling systems with a floor-level air supply are currently underway and new stratification correlations that take account of a cooled ceiling will be developed and implemented in a later version of EnergyPlus.

6. Acknowledgements

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7. References

[1] F. Bauman and A. Daly, *Underfloor air distribution design guide*, ASHRAE, 2003. ISBN: 1-931862-21-4

[2] Center for the Built Environment, *Underfloor Technology Case Studies*, University of California Berkeley, USA: Center for the Built Environment, 2007. www.cbe.berkeley.edu/underfloorair/casestudies.htm

[3] F. Bauman, T. Webster, P. Linden, and F. Buhl, *Energy performance of underfloor air distribution*

Accepted by Applied Energy. doi:10.1016/j.apenergy.2011.02.014

systems, University of California Berkeley, USA: Center for the Built Environment, 2007. www.cbe.berkeley.edu/research/pdf_files/UFADpt1_UFADEplus_051107.pdf

[4] J. Lau and Q. Chen, “Energy analysis for workshops with floor-supply displacement ventilation under the U.S. climates,” *Energy and Buildings*, vol. 38, Oct. 2006, pp. 1212-1219. www.cbe.berkeley.edu/research/pdf_files/SR2008-DenverEPA.pdf

[5] T. Webster, F. Bauman, D. Dickerhoff, and Y. Soo Lee, *Case study of Environmental Protection Agency (EPA) region 8 headquarters building Denver Colorado,* University of California Berkeley, USA: Center for the Built Environment, 2008.

[6] Y. Lin and P. Linden, “A model for an under floor air distribution system,” *Energy and Buildings*, vol. 37, Apr. 2005, pp. 399-409.

[7] Q. Kong and B. Yu, “Numerical study on temperature stratification in a room with underfloor air distribution system,” *Energy and Buildings*, vol. 40, 2008, pp. 495-502.

[8] C. Chantrasrisalai, B. Ghatti, D. Fisher, and D. Scheatzle, “Experimental Validation of the EnergyPlus Low-Temperature Radiant Simulation,” *ASHRAE Transactions*, vol. 109, Jun. 2003, p. 13.

[9] J. Babiak, B.W. Olesen, and D. Petras, *Low temperature heating and high temperature cooling: Embedded water based surface heating and cooling systems.*, Federation of European Heating and Air-conditioning Associations (Rehva), 2007. ISBN: 2-9600468-6-2.

[10] Z. Tian and J.A. Love, “Energy performance optimization of radiant slab cooling using building simulation and field measurements,” *Energy and Buildings*, vol. 41, Mar. 2009, pp. 320-330.

[11] S. Wang, M. Morimoto, H. Soeda, and T. Yamashita, “Evaluating the low exergy of chilled water in a radiant cooling system,” *Energy and Buildings*, vol. 40, 2008, pp. 1856-1865.

[12] B. Olesen, “Radiant floor cooling systems,” *American Society of Heating, Refrigerating and Air-Conditioning Engineers HVAC & R Research*, vol. 50, Sep. 2008, p. 7.

[13] The David Brower Center, “The David Brower Center,” 2008. www.browercenter.org/

[14] TiFS, “TiFS Engineering Headquarters,” 2008. www.tifs.it/index.php/en/catalogitems/viewsede/

[15] DOE, “EnergyPlus: Building Technologies Program,” 2009. http://apps1.eere.energy.gov/buildings/energyplus/

[16] DOE, “EnergyPlus Input/Output Reference v3.1,” Apr. 2009.

[17] J. Huang, H. Akbari, L. Rainer, and R. Ritschard, *481 Prototypical Commercial Buildings for 20 Urban Market Areas*, Berkeley, California, USA: Lawrence Berkeley National Laboratory, 1991. http://gundog.lbl.gov/dirpubs/29798.pdf

[18] California Building Standards Commission, “California Title 24 - 2005,” 2005.

[19] California Energy Commission, “Time-Dependent Valuation (TDV),” *California Energy Commission: Time Dependent Valuation*, 2007. www.energy.ca.gov/title24/2005standards/archive/rulemaking/documents/tdv/index.html

Accepted by Applied Energy. doi:10.1016/j.apenergy.2011.02.014