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Performance analysis of an integrated UFAD and radiant hydronic slab system

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ABSTRACT

In this paper, an EnergyPlus 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 a typical overhead system and a typical UFAD system in the cooling season for the Sacramento, California climate. When compared to the overhead system, the integrated UFAD/Radiant system shows a 22–23% reduction in total energy consumption during the peak cooling months (June to August) and a 31% reduction in peak hourly electricity demand. When compared to the UFAD system, these reductions are 21–22% and 24% respectively. An investigation of the simulation results showed that the integrated UFAD/Radiant system also improves occupant thermal comfort and reduces thermal decay issues in the underfloor plenum.

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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 and operated 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 in a variety of configurations around the world [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 [3–8].

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 [9]. 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 [10–15].

Lately, with growing concern regarding 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 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. 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:

- Tighter indoor temperature ranges than are typical of TABS due to the slow response time of these systems.
- Reduced thermal decay issues in underfloor plenums.

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Thermal decay in the UFAD system is defined as the temperature rise of the conditioned air due to convective heat gain as it travels through the underfloor supply plenum. While air temperatures also increase between the air handler and the air diffuser in overhead systems, the small ductwork surface areas, high air velocities, and ductwork insulation mean that temperature changes are small enough to be ignored in these systems. This is currently the approach taken by whole building energy simulation tools. However, this is not the case in UFAD systems, where significant temperature changes occur due to larger heat transfer surface areas, lower air velocities, and the lack of insulation. This is particularly the case for perimeter zones which are often located a significant distance from the air inlet into the supply plenum. The important phenomena of thermal decay has a significant impact on the energy balance within the building. According to field measurements and computer fluid dynamic analyses [16,17], air warms significantly as it passes through the supply plenum, yielding undesirable and uncontrolled air temperatures at the diffusers. Thus, it is essential to model thermal decay effects in underfloor air systems.

The objective of this paper is to quantitatively investigate the thermal behavior of an integrated UFAD/Radiant system using whole building energy simulation software. Additional objectives include investigating how the integrated system affects: thermal decay; cooling season energy consumption; cooling season peak demand; and thermal comfort. Several existing buildings use a hybrid of UFAD and hydronic slab systems, such as the David Brower Center, Berkeley, CA, USA [18].

2. Methods

2.1. Simulation software

The UFAD/Radiant system (Fig. 1) was modeled using EnergyPlus v3.1 [19] which has been validated against experimental measurements and through comparative testing with the BESTEST suite [20]. For further research regarding validation of the tool and validation of individual modules, see [21,22]. This robust tool uses the industry standard heat balance method for calculating space loads [23]. The tool simulates the performance of the building and HVAC systems as a whole by calculating the thermal loads

to be satisfied in order to meet the required indoor conditions. EnergyPlus has a large selection of capabilities when compared to other currently available whole building energy simulation software [24]. EnergyPlus was selected for this study over other existing simulation tools primarily due to the following key features:

- Room air stratification: Unlike conventional overhead systems, UFAD systems yield a stratified room environment. The UFAD module in EnergyPlus divides the room space into a lower occupied zone and an upper mixed zone in order to model room air stratification. Previous research describes the UFAD modeling algorithms installed and validated in EnergyPlus [3,8].
- Explicit simulation of supply plenums: EnergyPlus has the capability to model each underfloor plenum as a completely separate zone (in series or parallel with other zones, or ducted directly to the air handler), performing all the heat, mass and energy balances needed to accurately simulate thermal decay.
- Radiant heat transfer: EnergyPlus assesses the heat balance of each surface, calculates the surface temperatures at each time-step and accounts for the radiant heat exchange between each surface and the internal loads. Considering that radiant heat transfer is an important factor in advanced systems such as UFAD and radiant, this feature is a significant advantage for this study.
- Simultaneous simulation of zone, system and plant: EnergyPlus performs the system and plant simulation, and the air and surface heat balances simultaneously. This allows for analysis of real-time interactions between these different components.

2.2. UFAD/Radiant model description

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). Thus, supply air passes through the interior portion of the supply plenum before entering the interior occupied lower sub-zone and the perimeter portion of the supply plenum. 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

Fig. 1. Cross-section of typical interior and perimeter zones on the middle floor of the building.

system that uses pulse-modulated airflow boxes for interior zones and reheat boxes with water-fin-tube coils for perimeter heating. Pulse-modulated airflow boxes cycle between fully open (e.g., design maximum airflow rate) and fully closed, rather than typical VAV boxes which throttle airflow using a damper. These boxes control airflow by increasing the duration of the 'on' cycle as cooling load increases, and vice versa. 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 (thermostat temperature).

Hydronic tubes at the center of the 150 mm thick ceiling slabs are used to actively cool the building mass. Recent experimental measurements indicate that room air stratification is maintained, even when a chilled ceiling surface (operating at similar temperatures of 20–24 °C) removes a significant proportion of zone cooling load compared to air supplied at the floor level [25]. 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.

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 dry-bulb economizer (a mixing box) and a cooling coil. A water-cooled chiller supplies chilled water to the AHU cooling coils (Fig. 2). 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. Although the real system would operate just one tower, these were implemented in the model as two separate towers due to a

modeling constraint: EnergyPlus v3.1 does not allow for two separate chilled water loops to be connected to one condenser loop. Thus, it was not possible for the same tower to supply both the heat exchanger (for the slab system) and the chiller (for the air system). 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 reheat coils in each zone. Variable speed pumps supply each water loop.

2.3. 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 variable-air-volume (VAV) overhead (OH) system and a UFAD system. Both are typical of current good-practice systems, using low-energy technologies such as a fan static pressure reset and outdoor dry-bulb economizers. Table 3 describes the common model parameters in more detail. 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 [3,8]. This paper compares the performance of the UFAD/Radiant model to these two models.

The modeled building has a floor plate area of 1859 m² (total floor area of 5576 m²) and an aspect ratio of 1.5. Each floor is composed of four perimeter zones (4.6 m wide), an interior zone, and a service core. These zones represent 28%, 56% and 16% of the floor area respectively (see Fig. 3). Strip windows are evenly distributed in the walls with a window-to-wall ratio (WWR) of 0.4. The use of shading devices was not investigated.

Table 1 describes the major model parameters. Where possible, all model parameters such as those related to geometry, construction, 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. Although each wall in the model consists of multiple layers of individual materials, for the sake of brevity Table 1 represents thermal properties by overall U-value. The solar heat gain coefficient of the windows is 0.3, typical of modern low-e windows. Infiltration rate per exterior surface area was 0.333 l/m² s. The model uses lighting, equipment and occupant load densities and schedules derived from DOE-2 prototype models [26] (Table 2 and Fig. 4). The occupant activity level, or the combined sensible

Fig. 2. Chilled water plant schematic. The dashed and dotted lines signify day and night operation respectively.

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Fig. 3. Overview of the floor plate of the model illustrating the thermal zones on each floor.

Table 1
General model parameters: constructions and materials.

Construction	Materials	Overall U-value (excluding air film resistance) (W/m ² K)
Exterior wall	Stone (25 mm) wall insulation (0.541 m ² K/W) Vertical air layer (0.157 m ² K/W) Gypsum (16 mm)	1.27
Roof	Built-up roof (9.5 mm) Lightweight concrete (152 mm) Roof insulation (2.7 m ² K/W)	0.31
Ceiling slab	Lightweight concrete (152 mm)	2.15
Carpeted ceiling slab ^a	Lightweight concrete (152 mm) Carpet (0.11 m ² K/W)	1.74
Raised floor ^a	Tate access floor panel (41 mm)	3.54
Suspended ceiling ^b	Acoustic ceiling tile (13 mm)	4.48
Windows	Low emissivity, air filled double glazing	1.65

^a Not present in the overhead (OH) simulation (run 1).

^b Not present in the UFAD/Radiant simulation, which does not contain a return plenum (run 3).

Table 2
General model parameters: internal loads.

	Lighting loads	Plug loads	Occupancy
Value	10.8 W/m ²	8.6 W/m ²	25.5 m ² /person
Radiant fraction	0.32	0.4	0.6

Table 3
General model parameters: HVAC system and plant.

Component/parameter	Description/value
Global sizing factor	20%
Fans	Variable speed supply and relief fans (70% fan efficiency, 90% motor efficiency, part load curve courtesy of Taylor Engineering, Alameda, CA, USA)
Static pressure reset	Yes
Supply air temperature set-point	15.55 °C
Outside air controller	Dry-bulb economizer
Terminal unit minimum airflow fraction	Minimum ventilation air
Occupied zone air heating set-point	21.1 °C
Occupied zone air cooling set-point	23.9 °C
Chiller	Water-cooled screw chiller (COP 5.26, performance curves based on DOE-2 Centrifugal/5.50COP [26])
Chilled water temperature set-point	7.22 °C
Cooling tower	Two speed
Boilers	Two staged forced-draft gas boilers (80% nominal efficiency, part load curve based on CBE estimate of DOE-2 forced draft curves)
Hot water temperature set-point	80.0 °C
Pumps	Intermittent, variable speed (90% motor efficiency, part load curve courtesy of Taylor Engineering, Alameda, CA, USA)
Domestic hot water	None

Fig. 4. Weekday schedule values for occupancy (top), equipment (middle) and lighting (bottom) loads.

and latent heat per occupant, was 139 W/person. The model uses minimum ventilation air requirements of 0.76 l/m² s for occupied spaces, according to Title 24 of the California Code of Regulations [27]. Table 3 describes the various HVAC and plant parameters and the sources of the performance curves. The model uses a time-step of 15 min. Smaller time-steps do not significantly affect the results, primarily due to the fact that time-dependent simulation input data is defined at hourly intervals (e.g., weather data, occupancy profiles, etc.). All of these model parameters are fixed in each run.

2.4. Parameters that vary between models

Table 4 illustrates the parameters that vary between models. The overhead (OH) and UFAD runs are used as a baseline for comparison with the UFAD/Radiant runs.

3. Results

3.1. UFAD/Radiant zone conditions

As with the OH and UFAD/Only systems, the UFAD/Radiant system maintains occupied zone air temperature within the dead-band range of 21.1 °C and 23.9 °C. However, it should also be noted that the UFAD/Radiant system maintains significantly lower mean radiant temperatures (MRT) than the other two cases, as Section 3.5 discusses. Fig. 5 illustrates the indoor conditions within a typical zone for the UFAD/Radiant system. The newly

Table 4
Run parameters.

Simulation run number	1	2	3
Short name	OH	UFAD/Only	UFAD/Radiant
HVAC 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

implemented control method operates the hydronic system to cool each slab until the bottom surface temperature (ceiling surface) reaches a set-point, in this case 20.5 °C. The slab then absorbs heat and its high thermal inertia causes it to warm gradually, reducing zone cooling loads on the air system throughout the day (Fig. 6). This indicates that proper utilization of slab thermal mass can significantly improve the cooling performance of radiant systems without additional installations. It should be noted that a cooler supply plenum removes cooling load from the room directly above the plenum, which is why the UFAD/Only case shows a lower zone cooling load than the OH case (Fig. 6).

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

Fig. 6. Average July/August midweek air system cooling load in the middle floor interior zone for runs 1–3.

3.2. Thermal decay

Since thermal decay (i.e., the temperature rise of the conditioned air due to convective heat gain as it travels through the underfloor supply plenum) is a phenomena that can be observed only in UFAD systems, the OH case (run 1) is not discussed in this subsection. Figs. 7–9 describe diffuser air flow rate, diffuser air temperature and convective heat transfer between the slab and the supply air for the interior and East zones for both the UFAD/Only and UFAD/Radiant cases.

Fig. 7 clearly illustrates the effects of thermal decay – the air temperatures reaching the diffuser are significantly higher than the 15.6 °C supply air temperature. The temperature rise across the underfloor plenum is similar between both the UFAD/Only and UFAD/Radiant cases (Fig. 7), indicating that the pre-cooled slab does not significantly reduce the temperature of the air reaching the diffuser. This is because the supply air temperature is lower than the slab set-point temperature. However, Fig. 8 shows that the convective heat transfer from the slab into the supply plenum air in the UFAD/Radiant case decreases 44% and 17% in the interior and East zones respectively (averaged over the period in the image), when compared to the UFAD case.

Fig. 7. Average July/August midweek diffuser outlet air temperatures in the interior and East zones for both the UFAD/Only (run 2) and UFAD/Radiant (run 3) cases.

Fig. 8. Average July/August midweek convective heat transfer rates between the slab and the supply air in the interior and East zones for both the UFAD/Only (run 2) and UFAD/Radiant (run 3) cases.

Fig. 9. Average July/August midweek airflows at the interior and East zone diffusers for both the UFAD/Only (run 2) and UFAD/Radiant (run 3) cases.

Fig. 9 shows that the combined effects of decreased cooling load and heat transfer between the slab and the plenum air reduce the required zone supply airflow when comparing the two systems. The supply airflow in the UFAD/Radiant case decreases 35% and 26% in the interior and East zones respectively (averaged over the period in the image), when compared to the UFAD/Only case. This indicates that the issue of the thermal decay is substantially resolved by employing the pre-cooling strategy offered by the integrated system.

Figs. 7–9 indicate that the improvement yielded by the UFAD/Radiant system decreases throughout the day as the pre-cooled slab absorbs heat. Furthermore, the pre-cooling strategy is less effective for zones that experience higher loads due to the finite thermal inertia of the slab. This is particularly the case when these loads occur later in the day, such as the south and west perimeter zones.

3.3. Energy performance comparison

The UFAD/Radiant system performs well when compared to more typical systems. Fig. 10 compares the summer energy performance of the baseline systems described in Table 4 above. The auxiliary, or ‘Aux’, category includes all pump and cooling tower energy consumption. The UFAD/Radiant case (Run 3) shows HVAC savings of 22–23% and 21–22% against the OH and UFAD/Only cases during the peak cooling months from June to August. Chiller and fan energy usage for cooling are also lower due to the slab pre-

Fig. 10. Cooling season HVAC energy consumption for each of the runs described in Table 2.

cooling strategy. These reductions are partially offset by increased auxiliary consumption and added perimeter reheat energy. The increase in auxiliary energy consumption is due to the additional running hours for the cooling tower and water pumps. The increase in heating energy consumption is due to an increased need for warm-up operation in the early morning period – when slab (and building) temperatures are lower due to the pre-cooling strategy and low outdoor air temperatures. It should be noted that the hydronic slab systems in perimeter zones do not operate during the swing season months (May and October) as the increased reheat and auxiliary (pumps and cooling tower) energy consumption exceeds the savings in cooling energy gained by the pre-cooling strategy. The energy reductions during the swing months are more modest because the slab does not pre-cool the perimeter and the auxiliary energy consumption is relatively higher compared to the chiller and fan savings during these months. Also, the UFAD/Radiant system does not yield very significant savings during weekends or holidays. The building is only partially occupied on these days and the HVAC systems operate over a shorter period (7 am–1 pm). Thus, the added energy required to pre-cool the slab is a relatively larger proportion of total HVAC energy consumption on these days when compared to weekdays.

3.4. Demand reduction

Aside from the monthly HVAC energy saving potential of the UFAD/Radiant system (Fig. 10), the time when electricity is used also changes. Due to the thermal storage effect of the concrete slab, the pre-cooling strategy shifts a portion of electricity use to the morning and night periods when compared to the OH and UFAD/Only cases. Fig. 11 illustrates that the additional electricity consumed by the pre-cooling strategy (in the morning and night periods) is minor compared to the reduction throughout the rest of the day and at peak demand. When compared to the UFAD/Only and OH cases, the UFAD/Radiant system reduces HVAC electricity consumption by 24% and 31% respectively at peak demand (4 pm) based on the time-dependent demand data for Sacramento [29]. This indicates that taking advantage of thermal inertia can be an important strategy to reduce peak energy demand.

3.5. Thermal comfort

Figs. 12–14 illustrate that the UFAD/Radiant system maintains lower occupied zone temperatures and mean radiant tempera-

Fig. 11. Average July/August midweek HVAC electricity consumption for each system (runs 1–3) with time-dependent source versus site energy ratio for Sacramento in red on the secondary axis with time-dependent source versus site energy ratio for Sacramento shown by the dotted line (on the secondary axis).

Fig. 12. Average July/August midweek mean radiant and occupied zone air temperatures for the middle floor interior zone for all three cases.

Fig. 13. Average July/August midweek mean radiant and occupied zone air temperatures for the middle floor West zone for all three cases.

tures than the OH and UFAD/Only baseline cases. This yields improved thermal comfort at all times throughout the day during the summer months (excluding the very early morning period for the interior zone, which is slightly overcooled). Alternatively, the UFAD/Radiant system could demonstrate further energy reductions (see Section 3.3) while maintaining similar thermal comfort levels by using a higher thermostat set-point than the other cases because of lower radiant temperatures. However, this research did not investigate such an operating strategy. 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. Fig. 12 also shows that the average occupied zone air temperature is always below the cooling set-point for the interior zone in the UFAD/Radiant case. Thus, for this zone, minimum ventilation air maintains the indoor air temperatures within the comfort range.

4. Discussion

A large number of discrete and continuous parameters affect the results of these simulations and it is not feasible to discuss them all in detail. However, over the course of this investigation

Fig. 14. Average July/August midweek mean radiant and occupied zone air temperatures for the middle floor East zone for all three cases.

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 2.7 m 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 floor plan buildings with large interior zones relative to the perimeter. It also follows that reducing perimeter cooling loads (using e.g., shading, improved glazing, etc.) would also favor the UFAD/Radiant system, as the thermal inertia of the pre-cooled slab would have a proportionately larger effect.

Overall, the large time constant associated with the radiant hydronic slab yields hour-of-day profiles for energy consumption and indoor conditions that are less oscillatory in nature than all-air HVAC systems. Thus, the UFAD/Radiant system would be most applicable to buildings that are continuously occupied and conditioned, such as hospitals, prisons, and 24-h manufacturing facilities.

4.1. Software limitations

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 efficiency curve types does not allow for accurate representation of boiler consumption at low part load. This affects boiler gas consumption during the low part load operation periods in the early mornings during the cooling season. 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 is 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 [28]). 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 (boiler) consumption seen when comparing run 1 to runs 2 or 3 in Fig. 10.

4.2. Further work

There are some 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. Although cost considerations were not studied in this research, it appears that the energy savings associated with the UFAD/Radiant system may not offset the additional initial cost of such a system in today's economic climate. However, further developments of this system are under investigation, such as a cooling system that can supply cool water to the slab throughout the day, as well as using 'free-cooling' to pre-cool 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. The ability of such a system to operate during the day (intermittently or continuously) would present a number of advantages:

- Further energy consumption reductions.
- Further reductions in peak demand.
- Improved energy performance during the swing seasons.

5. Conclusions

A simulation model of a novel HVAC system was created and compared to typical HVAC systems. In the Sacramento, California summer season, the UFAD/Radiant pre-cooling strategy shows an HVAC energy consumption reduction of 22–23% and 21–22% compared to the OH and UFAD/Only cases respectively. This system also reduces average July/August midweek peak demand (4 pm) by 24–31% when compared with the UFAD/Only and OH cases and shows an improved demand profile throughout the day. Furthermore, the UFAD/Radiant case shows improved thermal comfort when compared to more typical systems.

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