Title

Evaluation of cooling performance of thermally activated building system with evaporative cooling source for typical United States climates

Authors
Feng, Jingjuan
Bauman, Fred

Publication Date
2013-04-29

Evaluation of cooling performance of thermally activated building system with evaporative cooling source for typical United States climates [1]

Jingjuan (Dove) Feng and Fred Bauman

Center for the Built Environment (CBE)
University of California, Berkeley

April 29, 2013

[1] Taken from Advanced Integrated System Technology Development. 2013. *Final Report to CEC PIER Buildings Program, CEC Contract No. 500-08-044. Center for the Built Environment, University of California, Berkeley, CA. Full report available at http://escholarship.org/uc/item/8jb4f64f.*

ABSTRACT

Thermally activated building systems (TABS) are gaining popularity as a potentially energy efficient strategy for conditioning buildings. These systems can use large surfaces for heat exchange, and the temperature of the cooling water can be only a few degrees lower than the room air temperature. This small temperature difference allows the use of alternative cooling sources, for example, indirect/direct evaporative cooling, to possibly eliminate refrigerant cooling to reduce energy consumption. In addition, TABS allow the potential to reduce the electric power demand of the building if a night time precooling strategy is used. This research has investigated the application range of using slab-integrated hydronic radiant cooling (TABS) with a cooling tower providing chilled water as the primary way of conditioning the building. The objectives of this study were the following: 1) quantify the climatic limits of using evaporative cooling (cooling tower) for radiant ceiling slab system; 2) identify design options to expand the application; and 3) provide climate based advice for system design and operation.

INTRODUCTION

Thermally activated building systems (TABS) are gaining popularity as a potentially energy efficient strategy for conditioning buildings. These systems can use large surfaces for heat exchange, and the temperature of the cooling water can be only a few degrees lower than the room air temperature. This small temperature difference allows the use of alternative cooling sources, for example, indirect/direct evaporative cooling, to possibly eliminate refrigerant cooling to reduce energy consumption. In addition, TABS allow the potential to reduce the electric power demand of the building if a night time precooling strategy is used. This simulation study investigated the application range of using slab-integrated hydronic radiant cooling with a cooling tower providing chilled water as the primary way of conditioning the building. The objectives of this study were the following: 1) quantify the climatic limits of using evaporative cooling (cooling tower) for radiant ceiling slab system; 2) identify design options to expand the application; and 3) provide climate based advice for system design and operation.

We took the following approaches in this study: 1) survey of radiant system design experts to understand the current practices and design issues and limitations; 2) using energy simulation to evaluate the thermal comfort performance of the design.

RADIANT SYSTEM DESIGN SURVEY OF EXPERTS

In order for the study to best serve the interests of the design industry, we conducted a survey to get feedback from design practitioners, manufacturers, and top researchers who are experienced with radiant systems while we defined our study scope. This survey served to provide practical design and control information and to ensure the simulation models were configured to represent design practice to the extent possible.

The survey was designed to have two parts. The first part lists many of the key fixed system design parameters that we believe represent good design practice. We don't expect the simulation results to be highly sensitive to changes in these parameters and have therefore decided to keep them fixed during our simulation study. And the survey was used to make sure these assumptions are consistent with design practice. The second part lists the important parameters that we focus our attention on and the proposed range over which they will vary. The goal was to understand the important system design and operational parameters.

Summarized below are some key findings from the survey.

Radiant system types and applications

- Compared to embedded radiant ceiling systems, radiant floor systems are the most commonly used, and HVAC professionals have more experience designing them successfully. One survey respondent estimated that among all the embedded radiant projects, only 5 percent are radiant ceiling systems. Another survey respondent stated that he usually designs radiant ceiling based systems when the building is five stories or greater, and design floor based systems when the building is less than five stories.
- Radiant floor systems are a popular application in large rooms with high ceilings and when they can be used for the absorption of solar loads.

Radiant system design specifications

- Tube depth: The depth of the hydronic tubing in the slab depends on construction technique, code requirment and whether exploitation of the slab thermal inertia is considered. Also construction concerns are important: 2" depth of the tubes in the concrete is a code requirement in Canada to allow the minimum 1.5" concrete coverage to the reinforcing bars in the slab to meet fire ratings. When designing radiant ceiling systems, the normal practice is to tie the tubes for a radiant ceiling system to the tops of the bottom layer of reinforcing bars.
- Pipe diameter: The most commonly used pipe sizes are 1/2" , 5/8", and 3/4". The tubing diameter is a function of the size of the radiant zones, floor plate size and economics: on smaller radiant slab systems, 1/2" or 5/8" tubing is used. For larger zones, there is usually no special requirement, but it is common to use 3/4" tubing for additional gallons per minute (GPM) and increased loop length; this can minimize the number of manifold cabinets and their size.
- Tube spacing: The spacing between tubing generally ranges from 6 inches to 12 inches, on center, and spacing is defined by the bend radius of the particular tube diameter being used, and the desired average slab surface temperature . Where maximum cooling effect is desired, tighter tube spacing is used to get a very consistent slab surface temperature. Where the cooling load/output is less critical and a minor amount of thermal striping is tolerable, twelve inch spacing is feasible for economic reasons.

Ventilation system design

- The minimum capacity of the ventilation system is usually determined by requirements of IAQ and humidity control, whichever is highest. If minimal ventilation is used, chilled beams are one of the alternatives to provide additional cooling in high load spaces.

- The capacities of the air system are often increased as supplemental cooling if radiant system capacity is not adequate. This is especially true for perimeter zones.

System operation

- Radiant loop water temperature differential range is normally between 3-5 °C.
- Pump operation: in the radiant circuit, constant flow is usually used. Pulse width modulation is optional that can minimize run-time on pumps. The slow response time of slabs allows for pump on/off operation based on slab temperature sensor setpoint deadband.
- Condensation control: dew point sensors are used for making sure that supply water temperature is control to be 1-2°C higher than dew point temperature in the space.

Plant design and operation

- A cooling tower can be used for supplying cold water under suitable climatic conditions. Ground source heat pumps are another alternative that is often considered. However, more conventional design is seen in practice because of concerns about the limited capacity of cooling towers and the first costs of installing ground source heat exchangers. A chiller is the most frequently used source for chilled water. One operational strategy mentioned is to use the same chiller to supply warmer temperature chilled water to pre-cool the slab at night, and during the day to treat the primary air with colder temperature chilled water if dehumidification is needed. This strategy is considered as economically feasible and still being able to exploit the energy efficiency potential of supplying warm water.
- One rule of thumb for operating cooling towers for precooling is when night time outdoor temperature during summer falls below 63°F (17°C) and the wet-bulb temperature is lower than 59°F (15°C) , the cooling tower at night is a viable cooling source for slab cooling.

Load control strategies

- Controlling (shading) solar heat gain is important in the success of a radiant cooling project.

CLIMATIC APPLICATION RANGE OF TABS WITH EVAPORATIVE COOLING SOURCE

EnergyPlus v7.2 was used for the simulation study in Sacramento, San Francisco, Phoenix, and Atlanta. For each climate zone studied, a single-floor medium office building was simulated. The radiant cooling system was an exposed hydronic-based ceiling slab. Minimum ventilation air was provided in the baseline model by a dedicated outdoor air system (DOAS) with proper humidity control. For some climates where the evaporative cooling + radiant cooling system alone may not be able to ensure thermal comfort for the hottest periods, we explored options such as expanding the thermal comfort zone by increasing air movement with personal fans or increasing the cooling capacity of the ventilation system. For some severe climates, such as Phoenix, other design options were investigated.

CLIMATE ANALYSIS

The four climates we selected for this study are San Francesco, Sacramento, Atlanta and Phoenix. They represent climatic conditions ranging from mild to hot and with humidity level ranging from dry to relatively humid. Figure 1 plots the annual dry-bulb temperature and wet-bulb temperature ranges for the four climates.

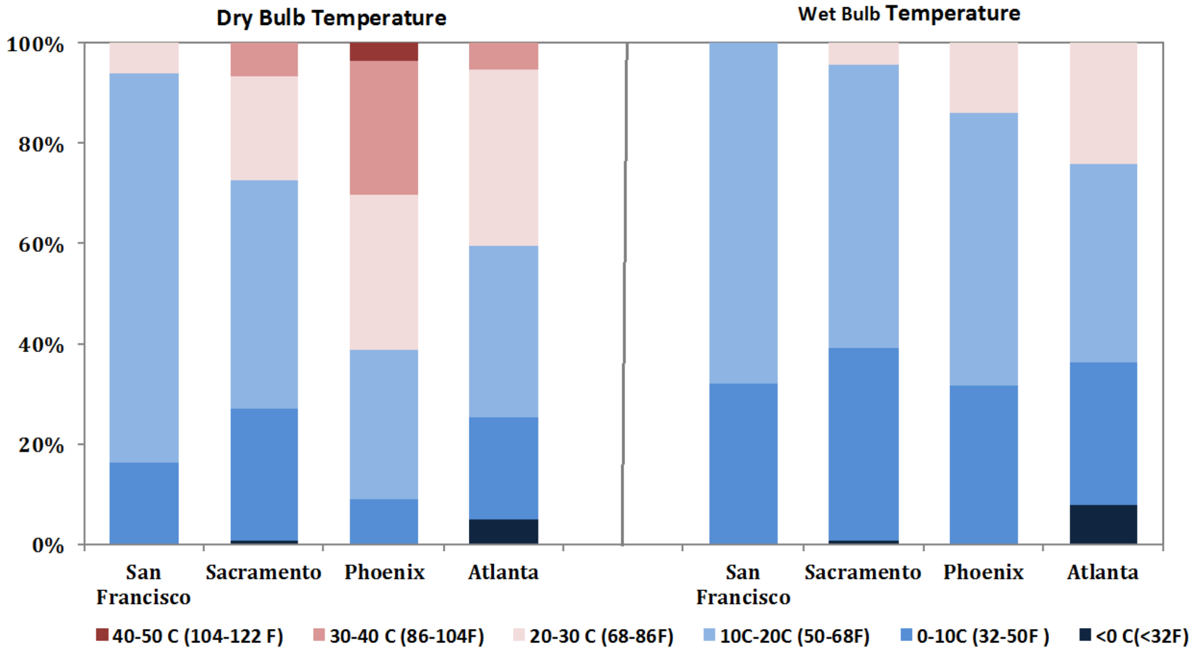
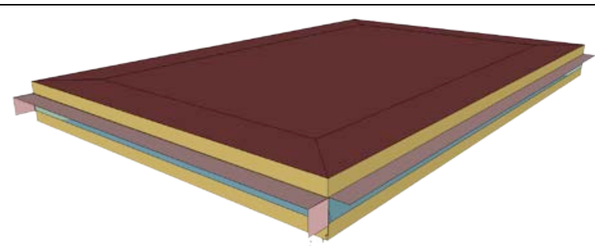


Figure 1: Dry-bulb and wet-bulb temperature ranges of the four selected climates

MODEL SPECIFICATIONS

For each climate, we developed a baseline EnergyPlus model, which is based on the prototype medium office buildings developed by DOE. The model envelope constructions are compliant with ASHRAE 90.1 2010 requirements (ASHRAE 2010a). One improvement in the prototype building was the shading systems. The survey results and literature study indicated that one key component of a successful TABS project is to control the solar heat gain. Since this study aims to evaluate the application potential of TABS integrated with evaporative cooling, shading systems are designed to the extent possible to minimize direct solar heat gain. Table 1 summarizes the baseline building model specifications, and Table 2 summarizes the simulated baseline radiant system specifications.

Table 1: Model specifications

Items	Descriptions
Model image	
Building and Internal load	Single floor 5-zone model compliant with 90.1-2010

Solar control	Exterior fixed overhang for all façade, Exterior operable blind for west and east facade
Radiant system	Radiant ceiling TABS
Air system	Dedicated outdoor air unit with heat recovery
Cooling source	Cooling tower
Cold supply water control	Max (wetbulb temperature + 2°C, room dewpoint+1.5 °C)
Humidity control	Zone humidity ratio at 0.012 lb/lb
Radiant system operation	24 hours or when cooling tower is available

Table 2: Radiant system modelling specifications

Item	Description
System type	Concrete embedded radiant ceiling system
Tube depth	2” (0.0508 m) below concrete surface
Tube diameter	5/8” (0.0158m)
Tube spacing	6” (0.15m)
Radiant loop water temperature differential	5.4°F (3°C)

DESIGN AND CONTROL OPTIONS EVALUATED

For all climates, we started the analysis with the baseline model. For some climates where the base design alone was not able to ensure thermal comfort for the hottest periods, we explored other options such as expanding the thermal comfort zone by increasing air movement with personal fans, increasing the cooling capacity of the ventilation system, and alternative radiant cooling technology, i.e. lightweight embedded surface radiant cooling systems. Table 3 summarizes the design options evaluated.

Table 3: Evaluated system design and operating strategies

Notation	Strategies	Climates
Base	Radiant slab system + air system with design flow rate for ventilation and humidity control purposes	SF, Sac, Atl, Phx
Precooling only	Nighttime precooling only by utilizing thermal mass storage effect.	SF, Sac
Elevated Air	Enlarge thermal comfort zone by elevating air movement	Sac, Atl, Phx
EnhancedAirSys	Size of air system is increased to provide additional cooling capacity if radiant slab is inadequate	Sac, Atl, Phx
ESCS	Use lightweight embedded surface cooling systems instead of heavyweight TABS	Phx

Note: SF= San Francisco; Sac = Sacramento, Atl= Atlanta; Phx = Phoenix

Base design

Minimum airflow rate was provided in the base model by a dedicated outdoor air system (DOAS). The minimum airflow rate was determined by ventilation and humidity control requirements. DX coil was modeled for the DOAS system. Therefore, the base air system design has the capacity to supply air temperature as low as 55°F if necessary. To minimize energy consumption, enthalpy heat recovery system was also modeled. Evaporative cooling, i.e., cooling tower, was provided 24 hours per day when the following conditions were met: there was cooling demand from the space and the water provided by the cooling tower was more than 3°F lower than room air temperature. Condensation is very less likely to happen with the cold water supplied from a cooling tower and with dehumidification capability from the DOAS system.

Precooling-only strategy

In this design option, cold water is only available for 10 hours (from 8pm to 6am) at nighttime to pre-cool the slab. The night time cooling setpoint was set to 68°F, which means during the precooling period, the valves for each radiant slab zone were independently controlled to meet this set point. This strategy was always implemented together with other design options in the study.

Elevated air motion

The recently updated ASHRAE Standard 55 (ASHRAE 2010b) indicates that under warm conditions the thermal comfort zone can be enlarged with elevated air motion, which can be achieved via ceiling fans, personal fans or natural ventilation. The energy advantages of extending the thermal comfort zone has also been demonstrated (Hoyt et al. 2009). Since TABS + evaporative cooling are likely not able to guarantee stable indoor thermal conditions, we investigated the potential of using elevated air motion to expand the application of TABS.

Enhanced air system

In this design option, instead of supplying only minimum air for ventilation and humidity control, the cooling capacity of the air systems were increased to serve as supplemental cooling. The magnitude of enhancement depends on the amount of supplemental cooling needed for different climates.

Embedded surface cooling systems (ESCS)

According to the REHVA guidebook on radiant systems (2007), water-based embedded surface cooling systems (ESCS) are one kind of radiant systems with pipes embedded in plaster or gypsum board or cement screed, and they are thermally decoupled from the main building structure (floor, wall and ceiling) by the use of thermal insulation. They can be used in all types of buildings and work with heat carriers at relatively high temperature for cooling. Compared to the TABS, which have pipes embedded in the building structure (slab, walls), lightweight ESCS have less thermal storage potential, but can have higher cooling capacity because the achievable slab surface temperature can be closer to water temperature due to smaller thermal resistance between pipes and building surfaces. Figure 2 shows the schematic of the ESCS system and TABS.

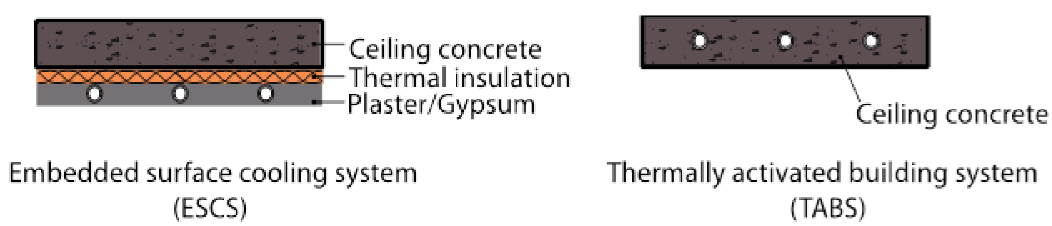


Figure 2: Schematic of lightweight embedded surface cooling system and TABS systems

THERMAL COMFORT EVALUATION

For evaluation of thermal comfort, we want to consider not only the total number of hours that the zone operative temperatures are outside of the thermal comfort zone, but also the severity of deviation from the comfort zone. In order to do this, the Method C PPD weighted criteria proposed in EN 15251 Appendix F (CEN 2007) was adopted here for long-term thermal comfort evaluation.

In this method, the time during which actual PMV exceeds the thermal comfort boundaries is weighted by a factor that is a function of the PPD.

Calculate weighting factor, wf, as shown below:

$$wf = \begin{cases} 0, & if \quad PMV_{limit\_low} < PMV_{actual} < PMV_{limit\_high} \\ \frac{PPD_{actual}}{PPD_{pmvlimit}}, & if \quad PMV_{limit\_low} > PMV_{actual}, or\ PMV_{actual} > PMV_{limit\_high} \end{cases} \quad (1)$$

Calculate the overall percentage of exceedance as the product of the weighting factor and the time for a characteristic working period during a year.

$$Exceedance_{warm}\% = \frac{\sum wf.time\ ,\ if\ PMV_{actual} > PMV_{limit\_high}}{\sum total\ characteristic\ working\ time}, \quad (2)$$

$$Exceedance_{cold}\% = \frac{\sum wf.time\ ,\ if\ PMV_{actual} < PMV_{limit\_low}}{\sum total\ characteristic\ working\ time} \quad (3)$$

In this study, PMV_{limit_low} =-0.5, and PMV_{limit_high} =0.5 were used.

In Appendix G of the same standard, the recommended threshold for acceptable deviation is that the percentage of exceedance in rooms representing 95% of the total occupied space is not more than 5% of occupied hours of a day, a week, a month and a year.

EXPANDED THERMAL COMFORT RANGE USING AIR MOTION

This section explains the impact of elevated air motion on expanding the thermal comfort zone. In Figure 3, we show the thermal comfort conditions of one of the hottest days in the cooling season in Sacramento. The left chart is the operative temperature profile over the day. Also shown are the lines that bound the thermal comfort zones. 79 degrees F is the thermal comfort high limit corresponding to still air conditions (0.15 meters per second (m/s) air movement), clothing insulation value (clo) of 0.5, and a 0.012 humidity ratio. At this condition, the PPD, reaches well above 10 percent. We can increase the thermal comfort high limit to 84 degrees F when air movement is at 0.8 m/s. In the right chart, we show the PPD profiles for the same day for both design scenarios. We can see that in the late afternoon, PPD value without elevated air movement goes higher than the 20 percent limit, but when air movement is provided, the PPD stays well below the 10 percent limit.

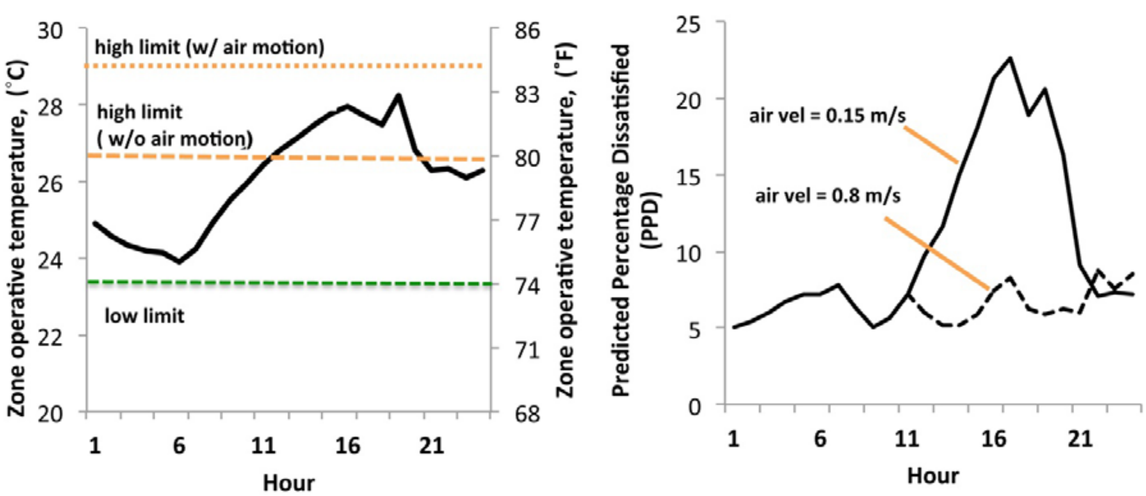


Figure 3: Example showing expanding thermal comfort range with air motion

RESULTS

The goal of this study was to investigate the application potential of using evaporative cooling as the primary cooling source for TABS, so we focused our analysis on warm discomfort during the cooling season.

San Francisco

San Francisco has a very mild climate with an average wetbulb temperature at 55 °F during the cooling season, and 100% of the time the wet-bulb temperature stays below 68 °F. For this climate condition coupled with well-designed shading system for the building, cooling demand was minimized in the simulated model. For San Francisco, we only evaluated the base design with pre-cooling only option, and the thermal comfort performance is quite satisfactory with hot exceedance level at 0%.

Sacramento

Sacramento features a warm and dry summer season with more than 10% of the time in a year having dry-bulb temperatures higher than 86 °F and an average wetbulb temperature at 60 °F during the cooling season. Weather analysis shows that the average diurnal wetbulb temperature difference during the cooling season is about 15 °F, and this indicates that Sacramento has a great potential for the precooling strategy.

For Sacramento, we investigated the following design options: Base case, base design + precooling only, with air system having 50% enhanced cooling capacity, with air system having 50% enhanced cooling capacity + precooling only. And for the all these four design options, we evaluated the thermal comfort performance of the system under two scenarios: with and without elevated air motion.

Figure 4 presents the thermal comfort results of all design cases. The red dash line is the 5% exceedance high limit required in EN 15251-2007. Figure 4 indicates that if cooling tower can be made available for 24 hours a day, the base design, TABS with minimum ventilation air, can achieve acceptable thermal comfort performance. If cooling was provided only at night by pre-charging the slab, the hot exceedance level is 5.8%, which is higher than the 5% threshold. However, if elevated air motion can be provided to the space, the exceedance level can be pulled down to 0.17%.

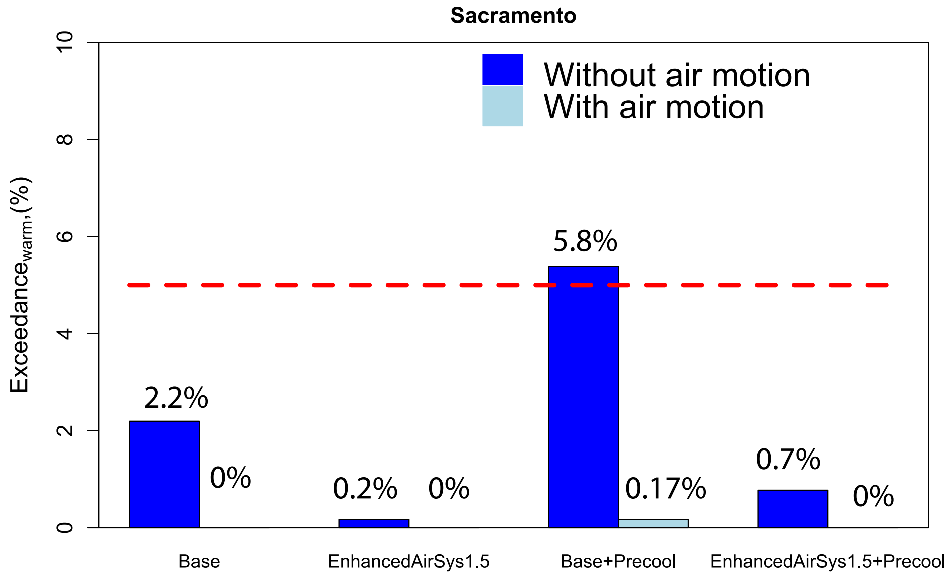


Figure 4: Exceedance of weighted PPD too warm for Sacramento

Atlanta

The climatic condition of Atlanta is warm and humid with more than 20% of the time having outside wetbulb temperatures higher than 68°F during the entire year. For Atlanta, we investigated the following design options: base case and air system with 50% enhanced cooling capacity. And for all options, we evaluated the thermal comfort performance of the system for the cases with and without elevated air motion.

Figure 5 presents the thermal comfort results of the design options for Atlanta.

First, we can see that the base design created the level of hot exceedance level at 40.8%, which is way above the accepted high limit. However, if elevated air motion can be provided to the space, the hot exceedance level can be reduced to 4.8%. This means during those discomfort hours, a large portion of the time has temperatures between 79 °F to 84 °F, a temperature range that can be satisfied by increasing air movement in the space.

A second option to improve the design was to increase the cooling capacity of the air system by increasing design airflow rate for 50%. This can reduce the hot exceedance level to 6.4%, which is still too high.

The last option we evaluated was to enhance cooling capacity of air system plus elevated air motion. This design can almost eliminate the hot discomfort for the whole cooling season.

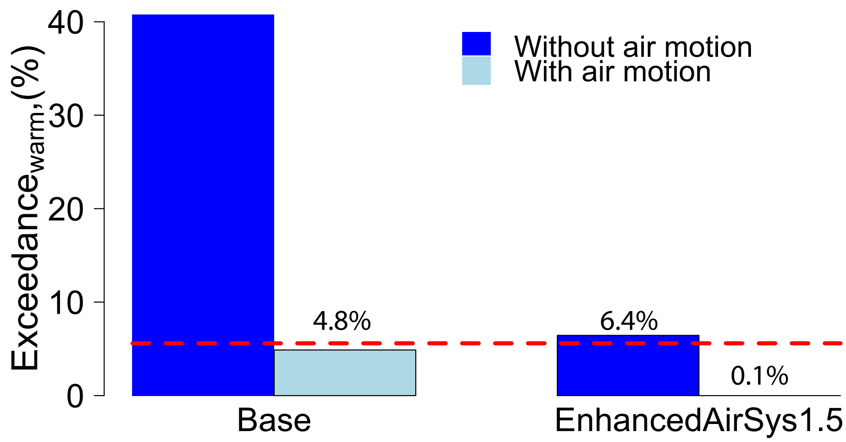


Figure 5: Exceedance of weighted PPD too warm for Atlanta

Phoenix

Phoenix's climate features a hot and dry cooling season with more than 30% of the time in a year having dry-bulb temperatures higher than 86 °F and an average wetbulb temperature at 63 °F during the cooling season. Weather analysis shows that the average diurnal wet-bulb temperature difference is about 6 °F and the differences are only 3°F during the hottest days. This indicates that precooling using evaporative cooling is not effective, because the cooling capacity of the cooling tower varies little between day and night times.

Figure 6 presents the thermal comfort results of the design options evaluated for Phoenix. We can see that most of the design options evaluated cannot satisfy the thermal comfort requirement. With the base design the level of hot exceedance level is 117%. The value can go higher than 100% because it is weighted PPD and 117% implies severe deviation from the thermal comfort range. If the cooling capacity of the system is augmented by triple the minimum air flow rate, the hot exceedance level is still 67.5%. If elevated air motion can be provided to the space, the exceedance level can be reduced to 29.3%, which is still much higher than the 5% high limit.

An alternative design option we evaluated was replacing the TABS with lightweight embedded surface cooling systems (ESCS), sometimes also called the plaster panel system. Compared to the TABS, the ESCS have higher cooling capacity because the thermal resistance between the radiant cooling surface and water pipe is smaller. As indicated in the climatic analysis, the cooling tower capacity varies little during day and night, so it is more effective to maximize the cooling capacity of the radiant system during occupied hours by minimizing thermal resistance between pipes and room space. The last design option employed the ESCS systems plus an air system with design cooling airflow rate three times the minimum requirement. This design alone cannot satisfy the thermal comfort requirement, but has reduced the discomfort level to 26.6%, and if elevated air motion is provided, the discomfort level can be further reduced to 4.4%.

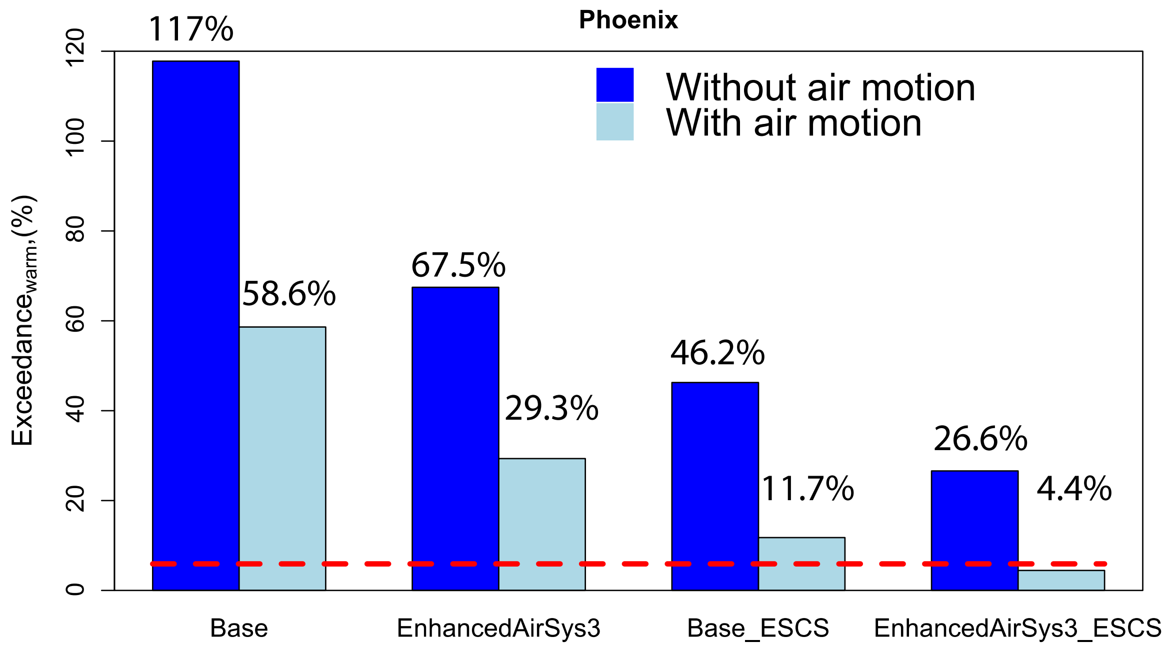


Figure 6: Exceedance of weighted PPD too warm for Phoenix

CONCLUSIONS

The conclusions from the simulation study are the following:

- In general, elevated air motion can dramatically reduce the hot discomfort level for most of the design options and climates.
- Evaporative cooling can be used as the only cooling source for the TABS in San Francisco. Hot discomfort can be eliminated by only precooling the slab.
- Sacramento is a good candidate for implementing a precooling strategy with TABS. This is because the cooling capacity of the cooling tower varies significantly during day and night due to the large (average 15°F) diurnal wet-bulb temperature difference.
- In Sacramento, hot thermal discomfort can be reduced from 5.8 % to 0.17% by providing elevated air motion for the base design using precooling only strategy.
- The base design option in Atlanta creates a 40.8% hot exceedance level. However, with elevated air motion, the hot exceedance level can be dramatically reduced to 4.8%. For Atlanta, another design option evaluated is to enhance the cooling capacity of the air system by increasing the design air flow rate to 1.5 times the minimum ventilation flow rate. This can reduce the hot exceedance level to 6.4%, and with elevated air motion, hot discomfort can be eliminated.
- Precooling with evaporative cooling is not effective in Phoenix, because the cooling capacity of the cooling tower varies little between day and night times during hot summer days.
- For Phoenix, using evaporative cooling as the primary cooling source for TABS cannot satisfy the thermal comfort requirement unless the cooling capacity on the air side is significantly enhanced. However, the use of an ESCS systems plus an air system with

design cooling air flow rate tripled the minimum requirement can reduced the discomfort level to 26.6%, and if elevated air motion is provided, the discomfort level can be further reduced to 4.4%.

One final note is solar load control is crucial to the success of all the design options. All the results above are based on simulating the building models that have complied with ASHRAE Standard 90.1 2010 and the buildings were configured to be very well shaded to minimize solar heat gain.

REFERENCES

CEN. 2007. *EN 15251-2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. European Committee for Standardization .

ASHRAE. 2010a. *ANSI/ASHRAE/IES Standard 90.1-2010: Energy standard for buildings except low-rise residential buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. 2010b. *ANSI/ASHRAE Standard 55-2010: Thermal environmental conditions for human occupancy*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Babiak, J., B. Olesen, et al. 2007. *Low temperature heating and high temperature cooling_REHVA Guidebook*, Federation of European Heating ahd Air-Conditioning Associations.

Hoyt, T., K.H. Lee, H. Zhang, E. Arens, and T. Webster. 2009. Energy savings from extended air temperature setpoints and reductions in room air mixing. *Proceedings from International Conference on Environmental Ergonomics*, Boston, August 2 – 7.