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How High Can You Go? Determining the Highest Supply Water Temperature for High Thermal Mass Radiant Cooling Systems in California

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SUMMARY

Cooling demands are a major driver of energy consumption in buildings, and is mostly performed using systems based on the refrigeration cycle, an energy and cost intensive process. To investigate the potential of eliminating the refrigeration cycle from a building design in Californian climates, we created a single zone EnergyPlus model that uses a high thermal mass radiant system as the primary conditioning system, and that meets California's energy code requirements. On the cooling design day, we randomly selected the start and number of hours of radiant system operation, lighting and plug load power densities, and occupant density for a set of models to determine the supply water temperature (SWT) that maintained comfortable temperatures. About 67% of tested models required SWT at or above 18 °C indicating that high thermal mass radiant systems have a high potential to use less energy and lower cost cooling devices like evaporative cooling towers in most California climates.

INTRODUCTION

Heating, ventilation, and air-conditioning (HVAC) systems account for 44% of total building energy use in the USA in 2012 (EIA 2012). Much of this energy use is due to cooling demands, typically met by equipment using a refrigeration cycle. The refrigeration cycle is an energy intensive process and the installed equipment requires a high first cost and operational capital investment. The installed cost of chillers and other refrigeration devices can range from $375 to $8,875 USD per refrigeration ton in the USA (*Mechanical Costs with RSMeans Data* 2017). Thus, eliminating the refrigeration cycle from the building design can reduce both energy and initial and operating costs.

Radiant systems are an alternative HVAC system that delivers 50% or more of the design heat transfer through thermal radiation (ASHRAE 2016) and provides equal or better thermal comfort to occupants when compared to all-air systems (Karmann el al. 2017). We define high thermal mass radiant systems as in Raftery et al. (2017). These systems have larger heat transfer areas than all-air conditioning systems, can shift cooling requirements to more efficient night times hours, and can efficiently transport heat throughout the building (Babiak et al. 2007). Some implications of these benefits are that higher than typical supply water temperatures for cooling can be used and the operation of the cooling plant does not have to be concurrent with the occupied hours of the building. However, a recent report indicates that in North America mechanical designers rarely design cooling plants that generate higher water temperatures or operate them in night times hours when more favorable weather conditions exist (Paliaga et al. 2017).

This study uses whole building energy simulation to investigate how high supply water temperatures (SWT) can be delivered to high thermal mass radiant systems without causing occupant thermal discomfort. The results provide guidance to mechanical designers looking to use more energy efficient devices (e.g. cooling towers) that do not use the refrigeration cycle.

METHODS

Envelope description

We created a single zone EnergyPlus model that uses a high thermal mass radiant system as the primary heating and cooling system. EnergyPlus implements the full ASHRAE Heat Balance method (ASHRAE 2017) and has a validated radiant system module (Chantrasrisalai et al. 2003). The single zone's dimensions are 25 x 5 x 3 m with a total area of 125 m^2 and represents a middle floor of a large office building. There is one window without shading on one façade which represents the exterior wall. We parametrically varied the orientation of the exterior wall with four levels; North, East, South, and West. The opposite and the two side walls have an adiabatic boundary condition. The floor and ceiling are thermally interconnected to represent the heat transfer of a middle floor. We defined the exterior wall as medium thermal mass wall with three layers. The outside layer is normal weight concrete with thickness, thermal conductivity, specific heat, and density of 100 mm, 1.2 W/m·K, 800 J/kg·K, and 2,240 kg/m^3, respectively. The middle layer is an insulation layer with thickness, thermal conductivity, specific heat, and density of 59 mm, 0.03 W/m·K, 1,500 J/kg·K, and 15 kg/m^3, respectively. The inside layer is plasterboard with thickness, thermal conductivity, specific heat, and density of 13 mm, 0.16 W/m·K, 1,090 J/kg·K, and 800 kg/m^3, respectively. The total U-value of the exterior wall is 0.35 $W/m^2 \cdot K$. We defined the total U-value for the window as 2.0 $W/m^2 \cdot K$ and 0.25 for the solar heat gain coefficient.

The U-value for the window meets Title 24-2013 prescriptive energy requirements. The maximum window-to-wall ratio (WWR) allowed in the prescriptive requirements is 40% but in this study, we parametrically tested 20, 40, and 60%. High WWR ratios without shading are not common for radiant systems due to the limited maximum cooling capacity, and thus, we believe 60% represents a reasonable upper bound for WWR.

We kept the U-value for the exterior wall constant to simplify comparison of results among all climates and this meets the prescriptive requirements in most of the California climates. Climate zone 15 is the only climate zone where the U-value for the exterior wall is higher than the prescriptive requirement (i.e. underperforming). Climate zones one, three, six, and seven the U-value overperforms, and in the rest of the climate zones, the U-value is equal to Title 24-2013 requirements.

Internal gains

We randomly selected the lighting (LPD) and plug load power densities (PLPD) and occupant density (OD) for each model in this study. Table 1 shows the limits within which we randomly selected from these internal gains levels. Table 1 also shows the radiant fraction used in the simulations. The upper limit for the LPD is the minimum allowed in office building types in Title 24-2013. Non-regulated internal gains include PLPD and OD. We used the Title 24 Nonresidential ACM Reference Manual and the DOE large office prototype building model to inform limits on non-regulated loads (California Energy Commission 2016; Deru et al. 2011).

Table 1: Lower and upper limits in which internal gains for each of the model could be randomly selected.

Internal Gains	Lower Limit	Upper Limit	Radiant Fraction
Lights	5	8.61 W/m^2	0.72
Plug loads	5	12 W/m^2	0.5
Occupants	10	20 m^2/person	0.4

We assumed occupancy to be from 8.00 to 18.00. We defined ventilation rates as the maximum of 7.08 L/s per person or 0.07 L/s per m^2 as stated in Title 24-2013 plus a 30% increment to the airflow which is common practice for DOAS systems to receive credits under rating systems such as LEED (Paliaga et al. 2017; USGBC 2013). The ventilation system has dual temperature setpoints at 15 and 21 °C. We set the infiltration rate as 0.537 L/s per area of exterior surface (0.39 ACH) which reduces to a quarter of that value when the ventilation system operates to pressurize the building and in line with US commercial reference models (Deru et al. 2011).

Radiant system description

We parametrically varied some of the radiant system design parameters, others were randomly selected, and one was held constant. We varied floor/ceiling slab thickness, tube depth and spacing parametrically with three levels each. The levels for slab thickness are 0.2032, 0.2540, and 0.3048 m. The tube depth levels are 0.0508, 0.0762, and 0.1016 m. The tube spacing levels are 0.1524, 0.2286, and 0.3048 m. We defined the floor/ceiling concrete slab with thermal conductivity, specific heat, and density of 1.8 W/m·K, 900 J/kg·K, and 2,240 kg/m^3, respectively. We did not add commercial flooring to the floor slab.

We also randomly selected the radiant system operation start time and number of total operation time in a 24-hour period to test many different control strategy scenarios. We understand that every building is unique and may require different operation times of their HVAC system due to utility price tariff structure, availability and time-dependent efficiency of the central plant providing the cooling, or other constraints. The start time could vary from the integers 0-23 representing an hour from midnight to 23.00 while the operation time could vary from the integers 6-24. Lower values were not used because the obtained SWTs were unreasonably low. The total water flow rate was held constant at 0.759 L/s. The water flow rate ranged from 0.152 to 0.095 L/s for each tubing circuit, or 'loops', since the total number of loops in the slab depended on the tube spacing and ranged from six to nine loops. The maximum loop length was set at 114.3 m but may be less due to rounding to the next whole loop. We defined the mechanical plant with district cooling to supply the requested water temperatures to the radiant system.

Simulation description

Table 2 shows a summary of the design parameters that we varied for each of the models. We allocated five 'factor levels' for the randomly selected design parameters. Therefore, we created five models that are almost the same except in the randomly selected design parameters. We used the Python eppy package to create the set of models for this study (Philip 2016). In total, we created 22,314 single zone models.

Table 2: Summary of design parameters that were varied among the single zone models. We randomly lights, plug loads, occupant density, radiant system start time, and radiant system total operation time because these parameters can have a higher variance in building design. Other parameters usually have set dimensions in the building design.

Design Parameter	Levels
Climates zones	1 to 16
Building orientation	North, East, South, West
Window-to-wall ratio	20%, 40%, 60%
Lights	Randomly selected
Plug loads	Randomly selected
Occupant density	Randomly selected
Slab thickness	0.2032, 0.2540, and 0.3048 m
Tube depth	0.0508, 0.0762, and 0.1016 m
Tube spacing	0.1524, 0.2286, and 0.3048 m
Radiant system start time	Randomly selected
Radiant system total operation time	Randomly selected

We calculated the comfort bounds at operative temperatures of 22.3 and 26 °C. This corresponds to -0.5 to +0.5 predicted mean vote (pmv) at an air speed of 0.1 m/s, relative humidity of 50%, occupant metabolic rate of 1.15 met, and a clothing insulation of 0.65 clo. We used the upper thermal comfort limit of 26 °C with a tolerance of -0.25 °C as the stopping criteria for the search of the required SWT to the radiant system.

We initialized the SWT at 20 °C for each of the models. Then, we simulated each model using only the design day of its respective climate data. We used the 0.4% dry bulb temperature and mean coincident wet bulb temperature, i.e. Ann Clg 0.4% Condns DB=>MWB, design day for each of the California's climate zones. If the operative temperature in a zone was not between 25.75 °C and 26 °C, then we adjusted SWT per Equation 1 and the model was simulated again.

$$SWT_n = \begin{cases} SWT_{n-1} + \varepsilon * 0.6, & if\ \varepsilon < -0.25 \\ SWT_{n-1} + \dfrac{\sigma}{2}, & if\ -0.25 \le \varepsilon < 0 \\ SWT_{n-1} + \varepsilon * 0.4, & if\ \varepsilon > 0.25 \end{cases} \quad (1)$$

The subscripts *n* and *n-1* in Equation 1 represents the new and old SWT, ε represents the error, and σ the tolerance set at -0.25 °C. The error is calculated as the difference between the upper comfort bound and the maximum operative temperature during occupied hours found in the simulation. This is conceptually similar to a control strategy recently presented (Raftery et al. 2017). The only parameter changing between each simulation is the SWT to the radiant system. Everything else stayed constant.

Wet bulb temperature analysis

We also obtained the annual weather data for each of California climates to do a preliminary analysis of the wet bulb temperature (WBT) and compare it to the SWT results. However, WBT is not included in the weather file, so we calculated it using the Python module CoolProp (Bell et al. 2014). We then created a subset of the annual WBT to only include months May through end of October. We arbitrarily selected this period to only include the cooling season. We binned up the WBTs by hour for all hours. We repeated the same procedure to only include hours from 20.00 to 10.00, which are the hours with the lowest WBTs on a given day. Then we calculated the 99th and 90th percentile for each binned hour for the two range of hours. It is important to compare WBTs to SWTs because WBT is an important driver for cooling towers to generate cooled water. The lower the WBT the lower the cooled water and higher the percentage of building and radiant system designs that can provide comfortable temperatures for occupants.

Simplified model development

We split the results into two datasets to train (70%) and test (30%) two linear models and one nonlinear model to estimate the SWT. An estimate of the SWT is useful for designers to determine if radiant systems coupled with energy efficient cooling sources are feasible for their building design. In the first linear model, we only used the instantaneous heat gains to train the model. Heat gains are an important metric in the cooling load calculation and are an important metric in predicting SWT as shown in later figures (ASHRAE 2017). In the second linear model, we use the heat gains in addition to, WWR, slab thickness, tube depth and spacing, and radiant system total operation time. We used the random forest regression algorithm, with all the parameters used in the second linear model plus building orientation and radiant system start time, to develop the nonlinear model (Wright and Ziegler 2015). We excluded building orientation and radiant system start time from the linear model and added it to the nonlinear model because these cyclical parameters cannot be represented in a linear model but can be handle through random forest regression model and other nonlinear models. We used the R Statistical Software package *caret* to train the models with ten-fold cross validation (Kuhn 2008). We implemented a parametric grid search for the number of variables (2 to 8) that random forests could be split at each node. We used the root mean squared (RMSE) to evaluate and compare the two models expressed in Equation 2 plus the random forest regression model.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2} \qquad (2)$$

where n represent the total number of tested data points, y_i is the actual SWT, and $\hat{y}_i$ is the predicted SWT.

RESULTS

We created Figure 1 to show the range of the resulting SWT for each California climate zone. We created the boxplot to show the 5th and 95th percentile at the ends of the lower and upper whiskers, respectively. The box shows the interquartile range from the 25th and 75th percentile and the black horizontal line inside the box represents the median. Figure 1 also shows the maximum 90th and 99th percentile among the hourly binned WBTs as a red and green line, respectively. We only show the percentiles that pertain to all-hours. The lines show the maximum percentiles among the hourly bins, thus cooler WBTs will exist. Comparing the WBT and SWT data, as in Figure 1, will give us information on the feasibility of coupling radiant systems to cooling towers. For example, if the 99th wet bulb percentile (green line) is below the median SWT (black line) for a specific climate, then 50% of the tested models have a high potential to use cooling towers.
The results show a maximum SWT of 25.4 °C for cooling when looking at all simulated models. There were some instances in climate zone 1 where heating was needed for north facing building models. For context, climate zone 1, with Eureka as the reference city, has a cooling design day reference dry bulb temperature of 21.6 °C and mean coincident WBT of 15.2 °C. About 67% of the tested models required SWT at or above 18 °C. Only about 1.3% of the tested models required 8 °C or less. The 8 °C threshold is a typical water temperature for chilled water generated by a refrigeration cycle, though this is still far below the minimum recommended SWT for high thermal mass radiant system due to condensation concerns. An analysis of the SWT shows that most of the time lower temperatures occur for radiant operation of nine hours or less, indicating that the operation hours should be above nine hours to take advantage of higher than typical SWT for cooling for the vast majority of cases (i.e. 98.7% of the simulated).

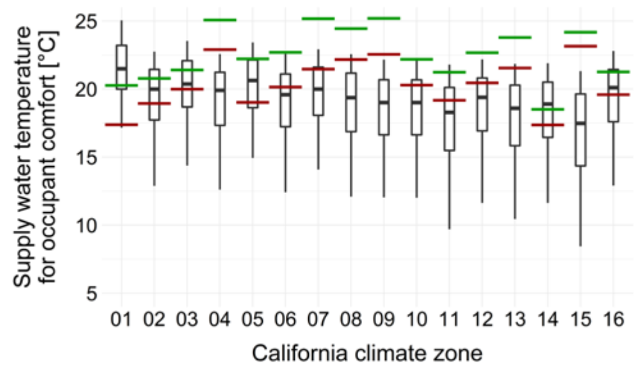


Figure 1: The range of supply water temperatures to maintain occupant thermal comfort for each California climate zone. The vertical lines in each climate represent the maximum 90th (red) and 99th (green) percentile among the hourly binned wet bulb temperatures for all-hours.

The WBT data for each of the California climates indicates that in most climates evaporative cooling towers are a potential alternative to provide cooling in the space while still providing comfortable temperatures during occupied times. There were 3,762 simulated models, representing 17% of the total, where SWT is higher than the maximum 99th percentile of the WBT for all climates. If the building design can strategically use the lower WBTs during the night (maximum 90th percentile), then this metric increases to 12,725 simulated models, representing 57% of the total.

Climate zone 15 is the only climate zone where the weather is more of a challenge to implement cooling towers. This climate, with reference city Brawley, has a design day dry bulb temperature of 43.9 °C and mean coincident WBT of 23.1 °C. It is important to recall that this is also where the simulated envelope had a lower U-value that required by code, which may have affected the results. However, all the wet bulb percentiles are high for this climate zone and will require more than improving the U-value of the envelope to successfully implement cooling towers coupled with radiant systems. Climates zones 4, 9, and 13 are also challenging climates but can incorporate building and radiant system design parameters modeled in this study in an optimized fashion plus the use of the lowest WBTs to provide comfortable temperatures in the zone.

Figure 2 (A) shows the relationship of the SWT and heat gains entering and generated inside the space. We obtained the instantaneous heat gains from lights, plug loads, occupants, solar, conduction through the exterior wall, ventilation, and infiltration using EnergyPlus's standard outputs. We binned the heat gains in increments of five to create the boxplot in Figure 2 (A). The boxplots in Figure 2 have the same meaning as in Figure 1. As expected, the more heat gains in the zone, the lower the SWT to the radiant system needed to maintain comfortable temperatures for the occupant. We also did a boxplot for building orientation, WWR, slab thickness, tube depth and spacing, and radiant system start time and total operation time to show the relationship to SWT in Figure 2 (B) to (H).

Equations 3 and 4 show the training results of the two linear models. The linear model displayed in Equation 3 only uses the instantaneous heat gains to predict the SWT whereas the linear model displayed in Equation 4 also uses the heat gains in addition to WWR, tube depth and spacing, and radiant system total operation time. Table 3 shows the RMSE for training and test datasets of the linear and nonlinear models.

$$SWT = -0.1461 * HG + 26.1 \quad (3)$$

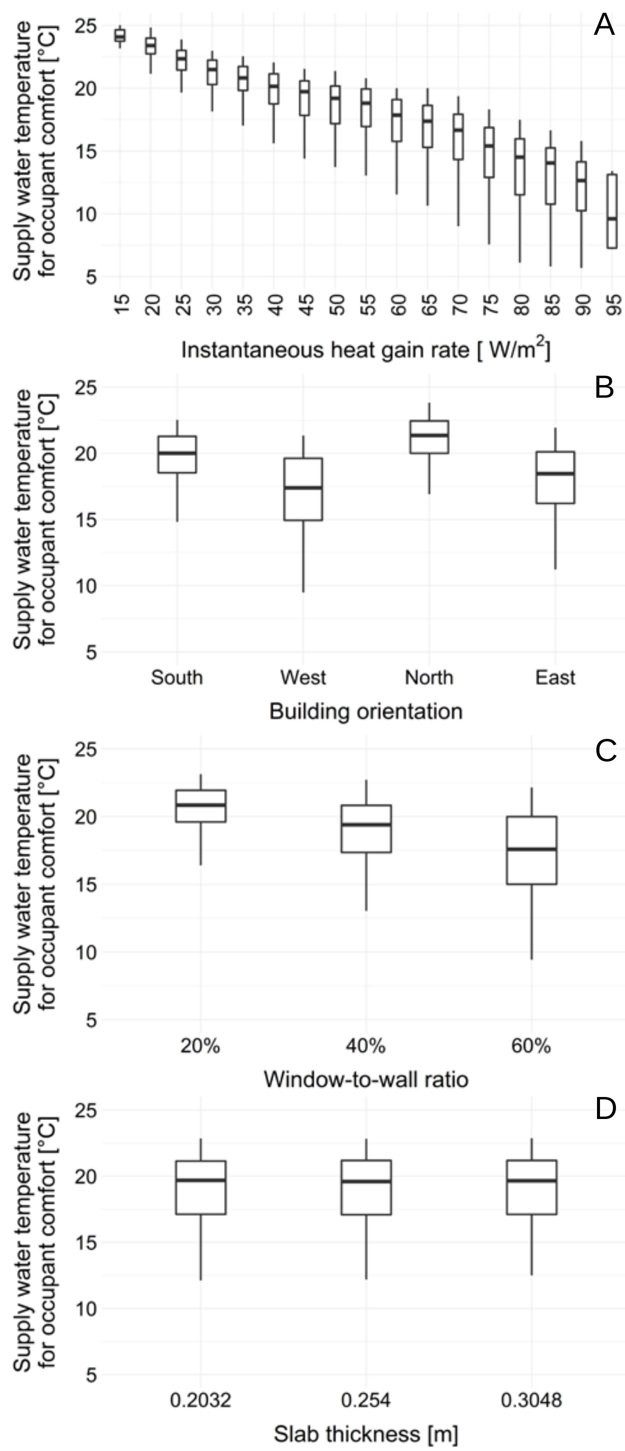
$$SWT = -0.1378 * HG - 2.06 * WWR - 4.35 * TD - 11.27 * TS + 0.3158 * OH + 24.6 \quad (4)$$

where *HG* is total instantaneous heat gains in the space, *TD* is tube depth, *TS* is tube spacing, and *OH* is radiant system operation hours.

Table 3: Root means squared error for training and testing of the two linear and one nonlinear models.

Model	Training RMSE	Testing RMSE
Equation 3	2.31 °C	2.33 °C
Equation 4	1.36 °C	1.33 °C
Random forest	0.86 °C	0.86 °C

Using more parameters for the linear model training reduces the RMSE by about 1 °C for both the training and testing datasets when compared to only using instantaneous heat gains. The RSME improves another 35 to 37% when using the random forests nonlinear regression model with all the parameters. According to the linear model initial linear model where we used more parameters, slab thickness (within the range) is not a significant predictor with a *p*-value of greater than 0.5 and thus not used in the final linear model. The rest of the parameters are significant predictors with *p*-values of less than 0.001. Designers can easily use either of the two linear models to estimate SWT requirements to the radiant system early in the design phase of the building. The random forest model is best used within a tool.



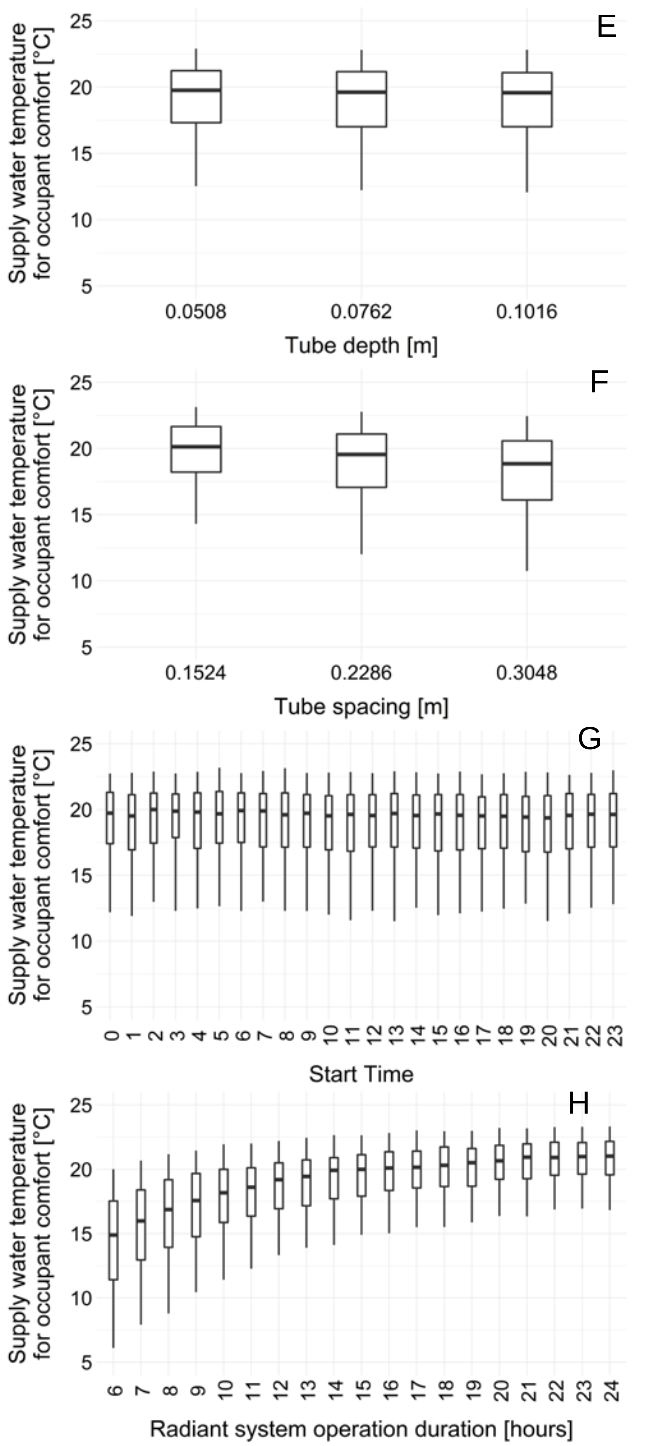


Figure 2: The supply water temperature for the radiant system to maintain occupant thermal comfort as a function of instantaneous heat gain rate (A), building orientation (B), window-to-wall ratio (C), slab thickness (D), tube depth (E), tube spacing (F), radiant system start time (G), and radiant system operation duration (H) in the thermal zone.

DISCUSSION

Radiant cooling systems offer great benefits over traditional all-air HVAC systems. This study demonstrates that they can maintain comfortable temperatures at higher than typical SWT. Furthermore, the mechanical cooling plants do not have to operate during the same occupied hours of the building due to the system's capability to store thermal energy in the building's thermal mass. These two aspects provide an opportunity to use evaporative cooling towers instead of the refrigeration cycle which is more expensive to install and operate. Cooling towers operate at a fraction of the energy cost. Chiller's COP ranges from 3 to 7 while cooling towers can range from 15 to 19 (Moore 2008). In the USA, initial costs range from $80 to $282 USD per equivalent refrigeration ton for cooling towers, compared to $375 to $8,875 USD per refrigeration ton for chillers (*Mechanical Costs with RSMeans Data* 2017). For context, the chiller cost is between $5/m^2 and $126/m^2 at a cooling load density of 50 W/m^2. This is sufficiently high that avoiding that initial cost using a cooling tower plus radiant design is likely a much lower overall initial cost option than other more conventional designs (e.g. an all-air system served by a water- or air-cooled chiller).

However, the feasibility of this design option is highly dependent on climate and peak design heat gain. In climate zones 1, 2, 3, and 14 the maximum 99th wet bulb percentile in hours 20.00 to 10.00 was lower than the required SWT in over 65% of the simulated models. Climate zones 7, 8, 9, 13, and 15 had the same metric at less than 10%. Bearing in mind that no specific design measures have been taken to reduce loads such as shading, increased insulation, improved glazing, and reduced internal loads, this implies that cooling towers coupled to radiant systems is a feasible design option in many cases. More challenging climates will require design strategies that go beyond code requirements to successfully use this approach.

There are other approaches to address cases where it is not feasible to further reduce the peak design heat gains. Elevated air speeds can provide occupant thermal comfort at higher indoor temperatures (Schiavon and Melikov 2008), which would increase the highest SWT that will still provide a comfortable environment. The elevated air speeds can also be beneficial in providing higher convection heat transfer with the surfaces in the zone during unoccupied hours. This will accelerate the cooling of the building's thermal mass in preparation for the occupied period of the building. The other alternative for difficult weather conditions is to provide a small supplemental chiller that can operate alongside the cooling tower (i.e. as an integrated waterside economizer) during extreme weather conditions to further reduce SWT to a value that will meet comfort criteria in the zone

Another important aspect to consider is the control of the radiant system during off-design periods. This paper performed simulations for only the design day of each California climate. The annual simulation will have different results because the radiant system will not operate the total number of hours designed for an extreme day. Raftery et al. (2017) presented a control strategy for high thermal mass radiant systems that can account for different SWT and hours of operation.

Nonetheless, in the early design phase, mechanical designers can use the simplified linear models developed in this paper to estimate the potential of providing cooling using only a cooling tower in radiant buildings. However, it is important to keep in mind the limitations of such models. There are only a few parameters that are vaguely linear to the SWT as shown visually in Figure 2 and there are limitations in addressing categorical or cyclical parameters (e.g. building orientation and radiant system start time). Nevertheless, simplified linear models are easy to develop and report results and thus the reason we used them in this study. A better approach is to create a nonlinear model that can easily consider the nonlinearities that exist between the data. We used random forests in this study and the RSME in the training and testing data was reduced significantly. The nonlinear model will need to be implemented into a tool to simplify its use. Regardless on which model designers use, the predicted SWT will need to be compared to the climate's respective WBTs.

Future work of this study will investigate the performance of cooling towers in more detail. This study did not directly connect the performance of a cooling tower to the radiant system needs. The results will be different since we did not consider cooling tower performance limitations, such as the tower design approach temperature i.e. difference between SWT and WBT, which is rarely lower than 2 °C, or the potential need for a heat exchanger and the associated difference in temperature incurred. We only used WBT data as a proxy to the potential of using these devices in conjunction with radiant systems for cooling in buildings.

CONCLUSIONS

This study investigated the highest supply water temperatures (SWT) to a high thermal mass radiant system that maintained comfortable temperatures in a single zone model. The models represent Title 24-2013 code compliant buildings in California climates. This study reports a median SWT of 19.7 °C among all data. These higher than typical SWTs open the possibility to use cooling towers in combination with radiant systems to eliminate the refrigeration cycle which is an energy and cost intensive process. Cooling towers can generate the required SWT during unoccupied periods of the building when WBTs are generally at their lowest. Some California climates can easily implement cooling towers in the building design while in other climates the building design will need to be more than just the minimum Title 24-2013 code requirements. We develop simple and advanced predictive models that can help designer assess the potential of coupling cooling tower to high thermal mass radiant systems. The linear models are the easiest to interpret. However, building data contains nonlinearities and alternative models need to be created to improve the SWT prediction. The successful implementation of this HVAC system will lower energy needs and greenhouse gas emissions significantly.

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