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Energy Flexibility and Sensitivity Analysis of High Thermal Mass Radiant Terminals

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ABSTRACT

High thermal mass radiant systems as a hydronic thermal mass activation method have many opportunities for cost-effective demand management. The system is regarded with the possibility of long-term transferring peak heating and cooling loads to off-peak hours and peak load reductions. This study conducted over 300,000 case calculations for a sensitivity analysis of load shifting parameters in radiant space conditioning systems across 16 climate zones in California, 14 different climatic cities outside California. The parameters analyzed include building geometric parameters (building length, width, window-to-wall ratio, orientation), internal heat source levels (from people, lights, plugs), control parameters (start and stop times), and the design construction of radiant terminals. A comparative analysis was also conducted across cities in different climatic conditions to explore the impact of climate on the load shifting capabilities of radiant space conditioning. The results of this study will aid in the formulation of strategies and the optimization design for load shifting in radiant cooling systems.

INTRODUCTION

The building sector is responsible for 40% of global carbon emissions in the world, which has been growing continuously at a rate of 2% to 3% per year (IEA 2022). The efficient utilization of renewable energy shows potential to substantially reduce carbon emissions of buildings (Kammen and Sunter 2016). However, the challenge is wind and photovoltaic power have strong volatility and intermittency. Adequate flexibility is necessary for the power system to ensure safe and efficient utilization, otherwise, it may increase the comprehensive cost of energy utilization by four times (Heptonstall and Gross 2021) and even triggering energy insecurity (Longden et al. 2021).

Energy flexibility in buildings is a cost-effective method to match renewable energy generation and actual consumption (O'Shaughnessy et al. 2022). Currently, there are roughly 2 billion air conditioning units in operation worldwide, making space cooling one of the primary contributors to the increasing electricity demand in buildings (IEA 2023). On the other hand, air conditioning loads present significant potential for load flexible management. Literature estimates the existing potential of commercial and residential air-conditioning systems to provide demand response across Australia, which shows the National Electricity Market could be reduced by up to 5.8% at which the peak occurs delayed by approximately two hours (Goldsworthy and Sethuvenkatraman 2020). Besides, the suitable management of the air conditioning load has the feasibility of utilizing 100% on-site photovoltaic energy supply for air conditioning energy consumption (Li et al. 2021).

The amount of building thermal mass that can be activated is the key factor determining the flexibility strategy's efficiency and performance without compromising indoor thermal comfort (Braun 1990). Xu et al. (2020) showed the load reduction capacity increases with an increase in the thermal mass weight, but there is a gain inflection point when the weight of the thermal mass exceeds 24.6 psf (120 kg/m^2). The main reason is that the thermal mass lumps up to a large bulk due to the limited convective heat transfer coefficient between its surface and the indoor air, making it harder to release its stored cooling capacity.

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Several previous studies have reported unsuitable pre-cooling strategies such as excessive cooling with the expectation of more energy storage capacity which can result in substantial increases in energy consumption due to ill-timed heat storage and release (Ding et al. 2022; Turner et al. 2015). Berardi et. al (2022) indicated the availability of thermal mass as the main limitation of using the building thermal inertia for energy flexibility strategies. Pacific Northwest National Laboratory (2021) has conducted an experimental investigation on thermal inertia characterization of commercial buildings where the results indicate that it may be sensitive to the type of HVAC system but not to the floor area or the location of zones.

Radiant systems with high thermal mass embedded tubes or panels within or under floors, walls, or ceilings through which heated or chilled water circulates (ISO 2012). In contrast to convective air conditioning systems, which indirectly store energy in thermal mass while maintaining air temperature, radiant systems with high thermal mass are utilized as a method for activating hydronic thermal mass (Olsthoorn and Haghighat 2017). Consequently, these systems are recognized for the potential to transfer peak heating and cooling loads to off-peak hours, achieving long-term reductions in peak load (Domínguez et al. 2017; Lehmann et al. 2007). A specific case study at Oak Ridge Laboratory demonstrated that active thermal mass cooling storage with insulation can shift cooling load for up to 8 hours (Jung et al. 2022). Under the same demand response strategy, the peak cooling load reduction for concrete radiant floors can reach up to 20%-34% compared to a convection air-conditioning system due to the cooling storage in the floor (Ahn et al. 2021). Radiant systems can utilize the thermal mass in the envelope to decrease peak cooling load through extra radiant heat transfer (Hu et al. 2020). The passive and active thermal mass could be simultaneously considered in the demand response of the radiant room. Furthermore, radiant systems benefit from the low-temperature heating and high-temperature cooling principle (Kazanci et al. 2016), the possibility of coupling with renewable heat sources and sinks (Kazanci and Olesen 2016; Olesen 2008), dealing with peak cooling load caused by solar radiation (Zhao et al. 2022).

Published papers and reports regarding radiant heating and cooling systems, encompass calculation methods (Ning and Zhang 2022), comfortable operating temperature (Rhee and Kim 2015), and cooling capacity (Shinoda et al. 2019). Nonetheless, the energy flexibility capabilities and parameter sensitivity analysis of radiant systems with high thermal mass have not been fully systematically disclosed. Many parameters that influence the energy flexibility of radiant cooling rooms, such as the meteorological parameters, room size, window-to-wall ratio, and the structure of radiant terminals. This work plans to analyze a series of parametric calculation cases, and then the energy flexibility characteristics of radiant cooling floor and ceiling systems can be systematically estimated. This research makes sense of the influencing mechanism of radiant systems regulating cooling loads via the thermal mass activation method.

METHODOLOGY

The heat exchange process in a radiant air conditioning room is complex, as shown in Figure 1(a). The radiant terminal, ventilation system, envelope, fenestration, interior partitions, internal heat sources, and air infiltration all contribute to the transfer or removal of heat within the radiant cooling room. These numerous factors together impact the energy flexibility of the radiant terminals. Additionally, the cold stored within the radiant terminals continues to influence the indoor heat transfer process, making its quantitative justification more complex. In this study, four different typical radiant terminals with high thermal mass (ISO 2012) were considered as shown in Figure 1(b), including embedded surface systems (ESS) and thermally activated building systems (TABS) for both floors and ceilings. ESS have an insulating layer that thermally decouples the floor and ceiling surfaces. TABS have the tubing embedded directly in the floor and ceiling structural slab.

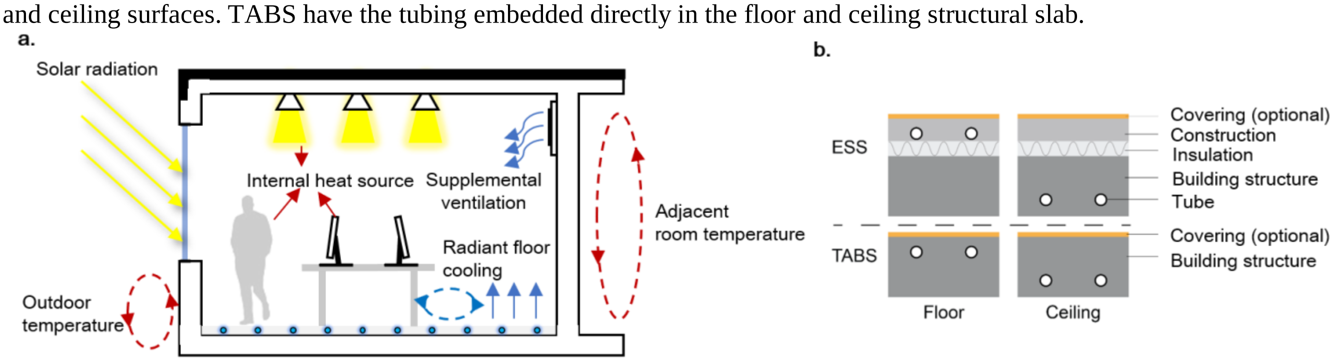

Figure 1 Schematic diagram of a radiant cooling room and terminals. (a) Heat transfer process, (b) Radiant terminal construction details.

Figure 2 presents a workflow to comprehensively investigate the impact of these variables on loadshifting performance. The quasi-random sampling method (Sobol 1976) was employed to generate parameter combinations within a multi-dimensional parameter space. This approach ensures that the parameter combination set accurately captures the true variability of the system. The parameters selected included building window-wall ratio, building orientation, room dimensions (width and length), indoor heat gain levels (jointly by the heat produced from people, lighting, plug loads), and the construction of four typical radiant terminals (thermal conductivity and thickness of the slab layer, depth of embedded pipes, and thermal resistance of the cover layer), and operating schedules (determined by duration time and start time), resulting in a total of 12,030 distinct case configurations per city. In this study, a total of 16 climate zones in California and 14 different climate conditions in U.S. cities outside of California were considered, and a batch calculation for 360,900 cases was conducted.

Then, the parameter combinations are used for batch calculations conducted collaboratively with Python and EnergyPlus. During the calculations, California's summer electricity peak and off-peak period time (from PG&E company's time-of-use rate plans), as well as typical summer day meteorological profile, are used as fixed parameters. For details on the selection of parameter ranges, climate zones and cities, and specific EnergyPlus model settings, please refer to the dissertation (Duarte 2020). The simulation results are collected and analyzed to produce statistical descriptions, and energy flexibility indicators are calculated. Each case preliminarily calculates the appropriate supply water temperature delivered to the radiant terminal, ensuring that the maximum operational temperature during occupancy does not exceed the thermal comfort limit.

Finally, the Sobol sensitivity analysis method (Sobol 1993) is used for global sensitivity analysis to examine the contributions of each input parameter to the output results. During the calculation of Sobol factors, an agent model was trained using batch simulation results, and Monte Carlo sampling was employed to enhance the accuracy of the calculated Sobol sensitivity indicators (Kucherenko et al. 2009).

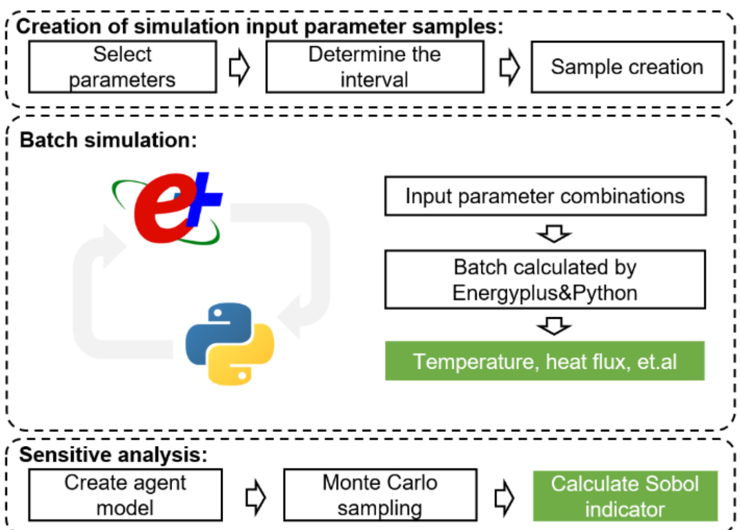

Figure 2 Flowchart for batch simulation and sensitivity analysis in this study.

The quantitative assessment of building energy flexibility serves as a crucial foundation for the application of auxiliary electricity regulation in buildings. Scholars have proposed indicators and methodological systems to quantitively evaluate demand flexibility, mainly encompassing aspects of power, energy, and duration. In this work, the relative value of peak shaving quantity to η_s valley electricity quantity (Hu et al. 2019) was selected to investigate the energy flexibility of radiant terminals. The calculated methods were as follows,

$$\eta_s = \frac{E_{off-peak} - E_{peak}}{E_{off-peak} + E_{peak}} \tag{1}$$

where, $E_{off-peak}$ is the amount of cooling energy supplied in the off-peak period, E_{peak} is the amount of cooling energy supplied in the peak period.

ILLUSTRATIVE RESULTS OF SAN FRANCISCO

This section delves into a comprehensive analysis using the actual electricity tariff rate curves specific to San Francisco, coupled with the region's typical meteorological conditions. These inputs serve as the foundational parameters to explore the energy flexibility potential of high thermal mass radiant air conditioning systems. Furthermore, this investigation extends to examine the sensitivity of various parameters that influence the load-shifting performance of these systems.

Statistical results of batch computation

Figure 3(a) presents the hourly cooling load curves forall simulated conditions in San Francisco. The shape of these cooling loads varies with different start and duration times of operation schedule, and the values of the curves differ according to the degree of heat gain in the room. Figure 3(b) displays the simulation results for room operative temperatures. It reveals that the operative temperatures for all conditions during the building occupancy hours from 8:00 to 18:00 consistently range between 71.6°F (22°C) and 82.4°F (28°C), indicating effective temperature management within the specified comfort range.

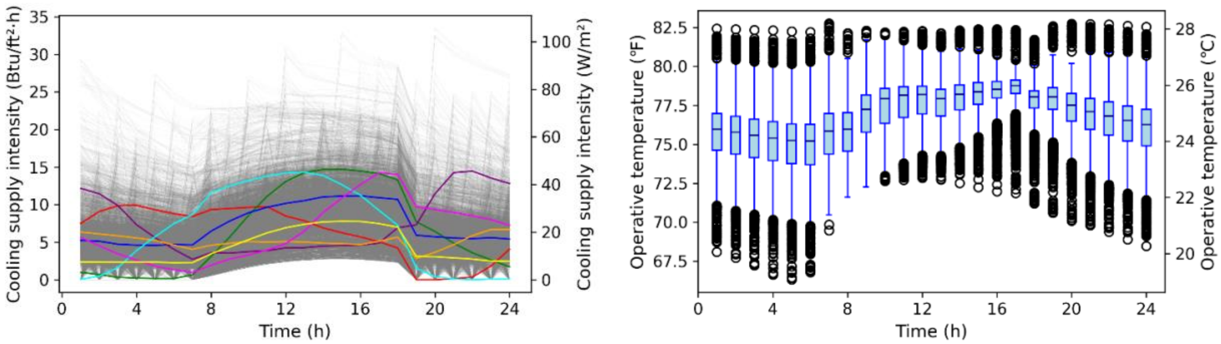

Figure 3 The results of batch simulation. (a) Cooling supply, (b) Operative temperature.

The operational duration for the simulation conditions ranges from 8 to 24 hours, and the start times also span every whole hour throughout the day. Consequently, the time series of the cooling supply varies for different cases. Figure 4 illustrates the hourly cooling load for cases with three distinct load shifting strategies. In the figure, the grey background area represents the peak electricity rate periods during the summer in San Francisco, which occur from 15:00 to 23:00. By employing Equation (1), the cooling loads during the peak and off-peak periods can be summed up to calculate the load shifting indicator, which indicates that a higher value represents more energy consumption during off-peak periods. The values obtained are 0.3263, 0.5944, and 0.1117 for the top, middle, and bottom load shifting strategy cases shown in Figure 4, respectively.

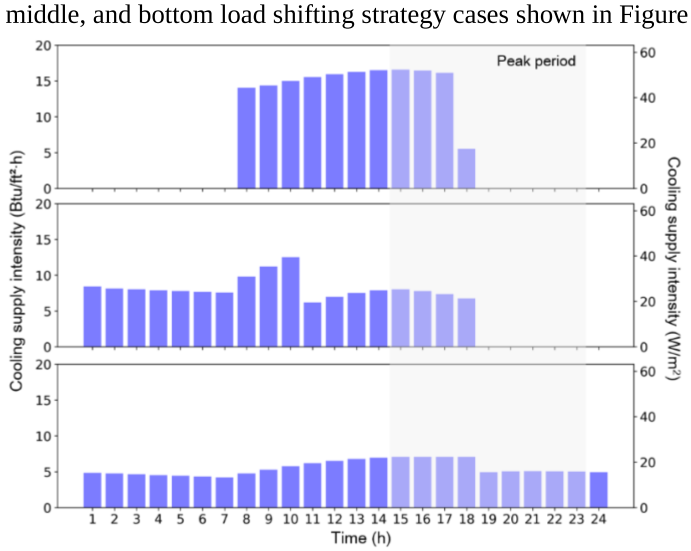

Figure 4 Hourly cooling load bar charts for three different operating modes.

Figure 5 presents box charts of load shifting and cooling supply for four different types of radiant terminals. It can be observed that there are no significant differences in the upper limits of load shifting achievable by the four types of radiant terminals, with the upper quartile values respectively being 0.809, 0.808, 0.716, and 0.810, and the maximum values 0.847, 0.861, 0.849, and 0.861. The overall energy consumption of the Floor ESS terminal is significantly lower than the other three types of radiant terminals. This is due to the insulation layer beneath the floor reducing the amount of heat transferred downwards compared to the other three types.

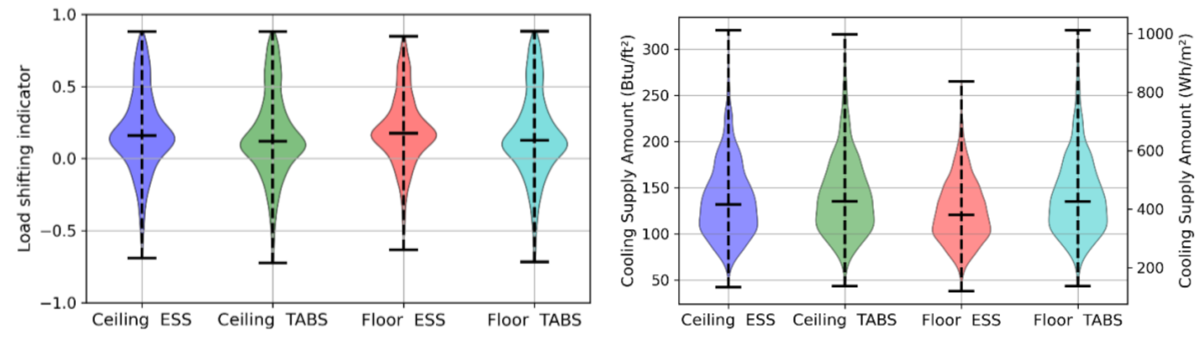

Figure 5 The violin plot of statistical results for four typical radiant terminals. (a) Load shifting, (b) Cooling supply amount.

Sobol sensitive indicators

Figure 6(a) presents the Sobol sensitivity analysis results for load shifting across four different types of radiant terminals. emphasizing that the start and duration times of the operational schedule are the two most critical factors for load shifting implementation. Figure 6(b) show the variation of the load shifting indicator with start times under each radiant terminal type. Notably, the indicators for all four types are at their lowest at a start time of 15:00, climbing to peak values between 22:00 and 24:00. Figure 6(c) depicts the impact of varying duration time on the load shifting indicator, demonstrating a significant decrease in the achievable upper and lower limits once the duration surpasses 14 hours. By combining the observations from Figure 6(b) and 6(c), it can be deduced that an optimal load shifting strategy within San Francisco's electricity rate structure would entail initiating start time between 22:00 and 24:00, while maintaining an operational duration of 8 to 14 hours.

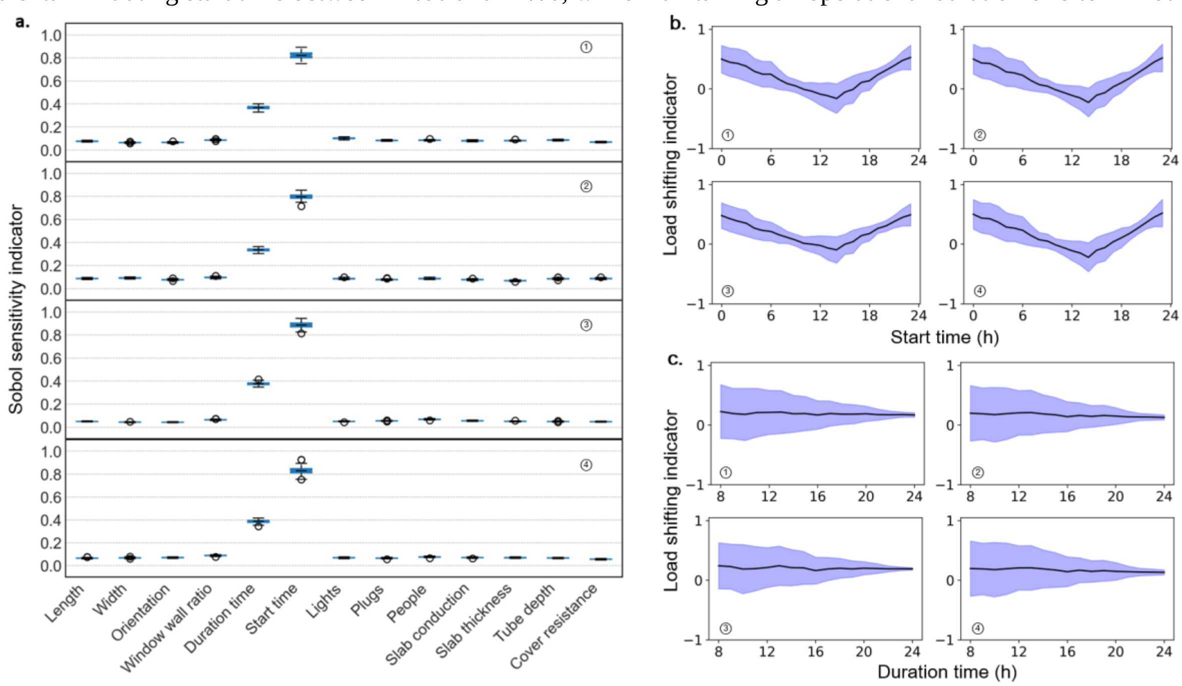

Figure 6 The results of Sobol sensitivity analysis and load shifting variations. (a) Sobol sensitivity indicator, (b) Variation with start time, (c) Variation with duration time. Symbols 1 to 4 refer to Ceiling ESS, Ceiling TABS, Floor ESS, Floor TABS.

When implementing load shifting strategies, the impact of strategy execution on energy consumption is also very important. Figure 7(a) shows the Sobol sensitivity parameters for various parameters affecting the cooling supply from batch computation results. It can be observed that compared to room geometric parameters, internal heat source levels, and thermal structural parameters of radiant terminals, the start and stop times exhibit lower sensitivity to energy consumption. This indicates that start and stop times are not the main parameters driving changes in cooling energy consumption. The correlation changes between start time, duration of operation, and cooling supply are depicted in Figure 7(b) and 7(c). It is evident that the cooling supply for all four types of radiant terminals generally increases slightly with longer operation durations, with the floor ESSterminal showing the largest increase, possibly due to the lower slab thickness. The start times do not show a clear pattern. In summary, for the electricity rate structure in San Francisco, initiating operations between 22:00 and 24:00 and controlling the duration between 8 to 14 hours presents a strategy that not only achieves optimal load shifting but also yields good operational efficiency.

To deepen investigating of parameter sensitivity in executing effective load shifting strategies, the start and duration times for all parameter combinations were standardized at 23:00 and 10 hours across all cases. Sensitivity analysis reveals that the room's geometric parameters and the intensity of internal heat sources hold similar importance, whether related to load shifting indicator or the cooling supply amount. These two sets of parameters demonstrated slightly greater sensitivity compared to the thermal construction parameters of the radiant terminals.

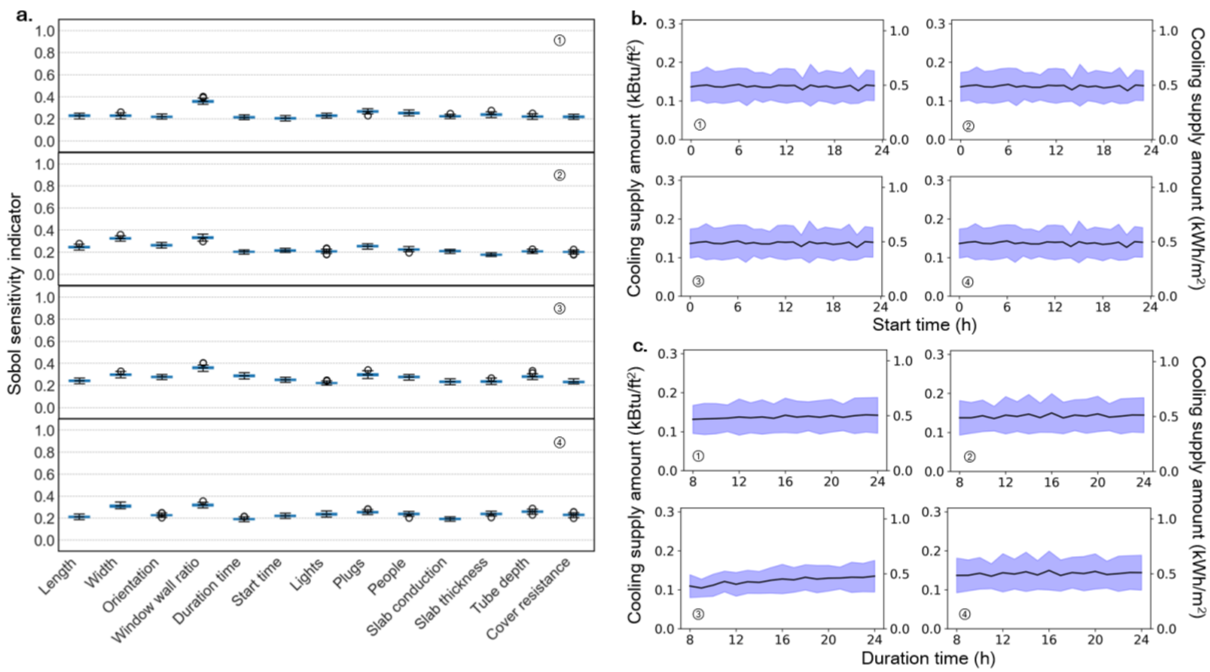

Figure 7 The results of Sobol sensitivity analysis and cooling supply amount variations. (a) Sobol sensitivity indicator, (b) Variation with start time, (c) Variation with duration time. Symbols 1 to 4 refer to Ceiling ESS, Ceiling TABS, Floor ESS, Floor TABS.

THE IMPACT OF ELECTRICITY RATE STRUCTURES

This section aims to explore the impact of different electricity tariff rate structures on the implementation of load shifting strategies for high thermal mass radiant terminals. For this purpose, different energy peak and off-peak periods are set by moving the start of the peak period earlier from 23:00 at night. For example, if the peak duration is 5 hours, then 18:00 to 23:00 is the peak period. A peak duration of 5-9 hours is a common Time-of-Use (TOU) electricity billing model currently used in the United States. When the peak duration extends beyond 12:00 noon continuing until the early morning, this represents a day-night time-differentiated electricity pricing structure that was common before large-scale integration of photovoltaics and other renewable energy sources into the power grid system.

As illustrated in Figure 8, the results for the load shifting indicator under various electricity rate structures are shown. It is evident from the graph that as the peak duration increases from 5 to 15 hours, the load shifting indicator consistently exhibits a declining trend. A significant decrease in the indicator's values, both in the maximum and the upper quartile, becomes particularly pronounced when the peak time duration exceeds 7 hours. Currently, California's utility companies have a summer peak rate duration of 9 hours (15:00-23:00). If the peak duration were to be shortened in the future, the proportion of load shifting achievable by radiant air conditioning systems could further increase.

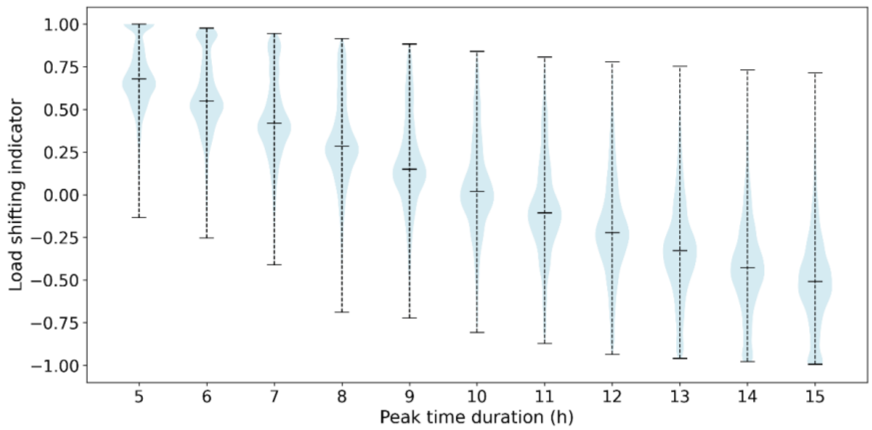

Figure 8 Statistical results of load shifting indicator for different peak time durations.

THE IMPACT OF CLIMATE

Climate is one of the main factors affecting the heat gains in buildings, which greatly influences the cooling load of a room. By aggregating the simulation data sets from 30 cities, we can analyze the impact of climate on the load shifting performance of high thermal mass radiant terminals. The calculated result was shown in Figure 9.

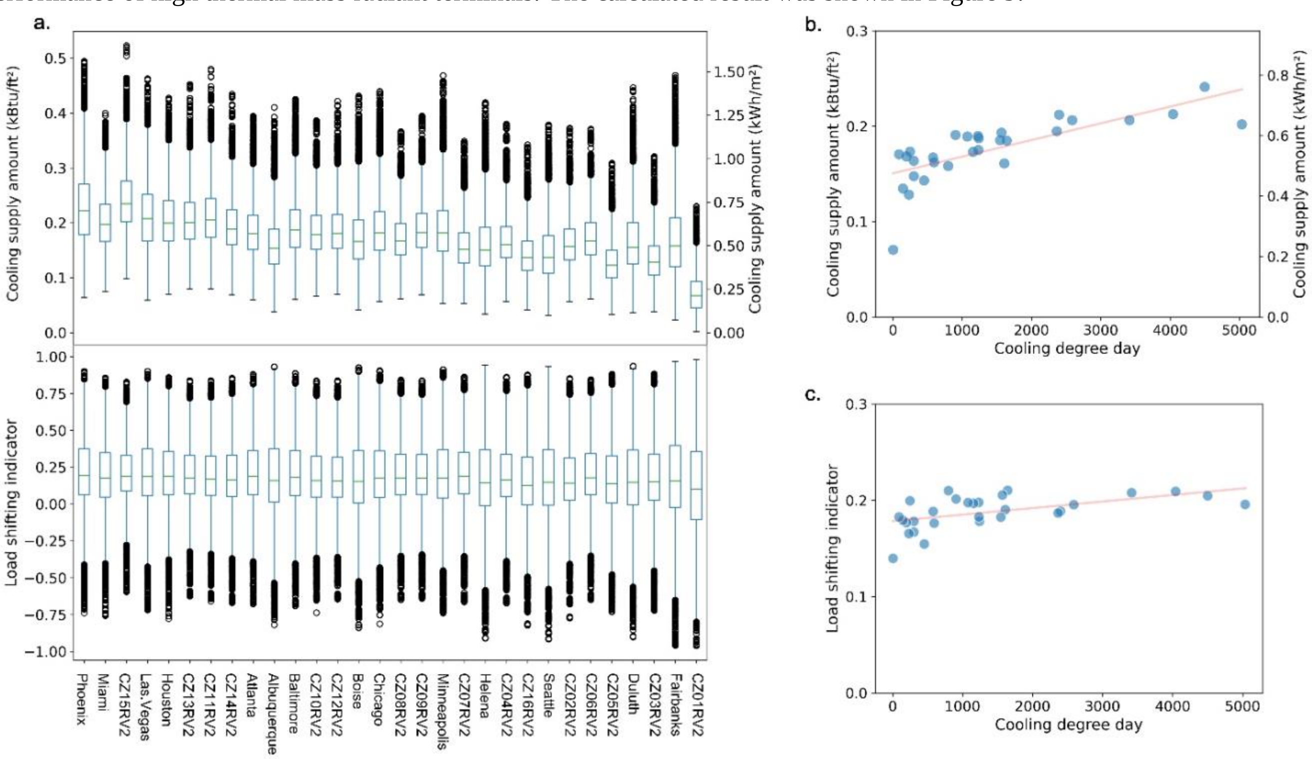

Figure 9 The collected results of cooling supply amount and load shifting indicator for all 30 cities and climte zones in California. (a) Box plot of values, (b) Linear regression plot of the average cooling supply amount for each city, (c) Linear regression plot of the average load shifting indicator for each city.

As shown in Figure 9(a), the statistical results of total daily cooling supply amount for all cases for the 30 cities are displayed, with each city arranged from right to left according to the magnitude of their 5-year average Cooling Degree Days (CDD), with the CDD data sourced from the Energy Star. As shown in Figure 9(b), there is a strong linear relationship between the cooling supply amountand CDD, showing a significant upward trend as CDD increases. For example, the region CZ03 where San Francisco is located has a CDD of 145, and its cooling supply amount ranges from the upper to lower quartiles at 0.039 Btu/ft² (0.12 kWh/m²) to 0.331 Btu/ft² (1.01 kWh/m²). Los Angeles, located in region CZ09 with a CDD of 1075, has its cooling supply amount ranging from the upper to lower quartiles at 0.062 Btu/ft² (0.19 kWh/m²) to 0.377 Btu/ft² (1.15 kWh/m²).

As illustrated in Figure 9(c), the degree of energy flexibility achievable by high thermal mass radiant terminals shows no significant correlation with CDD. Further aggregation of the load shifting Sobol sensitivity parameters across 30 cities and climate zone reveals that the duration time and start time continue to dominate across all 30 cities and climate zones. With an increase in CDD, the importance of duration time increases, but start time consistently holds a dominant position. The increasing significance of duration time is attributed to the fact that as CDD increases, the proportion of heat gained from transmission through the building envelope becomes a larger fraction of the total heat gain in buildings. This results in a smaller variance in total heat gain for different sets of parameter combinations based on internal heat sources, causing the statistical range of load shifting in areas with significant building heat gain to converge more rapidly with increases in duration time.

DISCUSSION

The results of this study highlight the critical role of start-stop times in the implementation of load shifting strategies in high thermal mass radiant cooling systems. Much of this effect can be attributed to the pre-calculation process implemented, which identifies the suitable water supply temperature. This approach helps minimize the impact of the thermal structures at the radiant terminals on energy flexibility and avoids the over-cooling issues that can arise from operating at fixed water supply temperatures for extended periods. Therefore, the thermal construction parameters of radiant terminals, which significantly influence heat transfer from the water side to the indoor side, exhibited insensitivity in terms of energy flexibility.

This study did not explore the potential effects of different control algorithms on the energy flexibility of high thermal mass radiant terminals, nor did we conduct extensive sensitivity analyses for various parameters that may affect these results. In addition, it is crucial to note that if the thermal mass contained in the radiant terminals is insufficient, it may lead to a significant deviation between the practical results and those observed in this study.

In response to these research gaps, future research should focus on exploring the effectiveness of different control algorithms and investigating the minimal thermal mass required under various load shifting signal scenarios. Such research would not only deepen the understanding of the thermal dynamics of high thermal mass radiant systems but also improve their application in building energy management systems.

CONCLUSION

In this study, the start and stop times determine the energy flexibility performance of high thermal mass radiant terminals. Moreover, the impact of start and stop times on the total energy consumption is relatively minor compared to other parameters. As the structure of electricity tariff rates includes an increased peak time, the upper limit of load shifting gradually decreases. A warmer climate does not lead to changes in the upper limit of load shifting indicators. This implies that with adequate thermal mass at the radiant terminals and the implementation of effective control strategies, efficient load shifting can be achieved.

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