Energy and Buildings 30 (1999) 127–138

Energy and peak power savings potential of radiant cooling systems in US commercial buildings

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Abstract

The paper describes a parametric study developed to estimate the energy and peak power savings potential of radiant cooling systems in commercial buildings in the US. The study is based on the numerical modeling of a radiant cooling system and an all-air system at different locations in the US. The results show that a building equipped with a radiant cooling system can be operated in any US climate with low risk of condensation. For the office space examined in the study, employing a radiant cooling system instead of a traditional all-air system can save on average 30% of the energy consumption and 27% of the peak power demand due to space conditioning. The savings potential is climate-dependent, and is larger in retrofitted buildings than in new construction. © 1999 Published by Elsevier Science S.A. All rights reserved.

Keywords: Peak power; Radiant cooling system; Commercial building

1. Introduction

Cooling of non-residential buildings contributes significantly to electricity consumption and peak power demand. Most of the building conditioning systems currently in operation are all-air systems, meaning that they employ air not only for ventilation, but also as a heat transfer medium. Radiant cooling systems separate the cooling and ventilation tasks of a building conditioning system. By employing water as a heat transfer medium, radiant cooling systems reduce the transport energy and peak-power requirements due to building conditioning. The elimination of air recirculation allows radiant cooling systems to reduce indoor air velocity, thus reducing draft and improving indoor comfort [1].

On the downside, radiant cooling systems require well-tuned control strategies to maintain the indoor moisture levels in a tolerable range and to avoid surface condensation during the cooling season. In buildings conditioned by radiant cooling systems humidity control is essential not only for the time the building is occupied but also for the time of pre-cooling the space and for some time after hours. This additional use of the ventilation system increases the energy consumption of the conditioning system, therefore reducing the energy savings achieved through the use of radiant cooling.

This paper proposes the following.

(1) An investigation of the conflicting effects of the dehumidification and cooling controls of the radiant cooling system on the energy consumption and peak power demand of the system in representative US climates.

(2) An estimate of the potential for energy and peak power savings of the radiant cooling system as compared to an all-air system providing similar indoor conditions.

The results of the paper are based on RADCOOL [2] and DOE-2 [3] simulations. The program RADCOOL was designed to simulate the dynamic thermal performance of hydronic radiant cooling systems in a numerical test room. RADCOOL also simulates the moisture balance in a room and evaluates the potential risks of condensation during cooling mode.

2. Methodology

An office space in a basecase office building was simulated in RADCOOL as conditioned by a radiant cooling (RC) system employing two ventilation strategies. The same office building was modeled in DOE-2 as conditioned by a variable air volume (VAV) system during occupancy hours and a constant volume system (CV) at night. This all-air system was designed in such a way that

PII: S0378-7788(98)00080-2

the indoor air temperature and humidity ratio during occupancy hours, and the outside air ventilation flow during the whole day, be the same as those for the RC system. Estimates were made for the conditioning energy and peak power demand of the two systems, and then compared. This procedure was repeated for several US locations. Due to RADCOOL limitations regarding simulation time, the parametric study was based on calculations for a few US locations only, and for two weeks of climate data for each location.

2.1. Basecase building and office space

The basecase building selected for the study is rectangular and oriented with its longer facade 45° east of north (see Fig. 1) [4].

The basecase office space MBC2 is situated in the middle of a facade and has one exterior wall oriented 45° west of south. The office is rectangular with an area of 22.5 m^2. The window area of the facade represents 20% of the floor area.

The building structure modeled represents an office building complying with the California Title 24 building standard [5]. The facade consists of a curtain-wall construction with the opaque part having a U-value of 0.45 W/m^2 K, and double-pane windows with a center-of-glass U-value of 1.31 W/m^2 K.

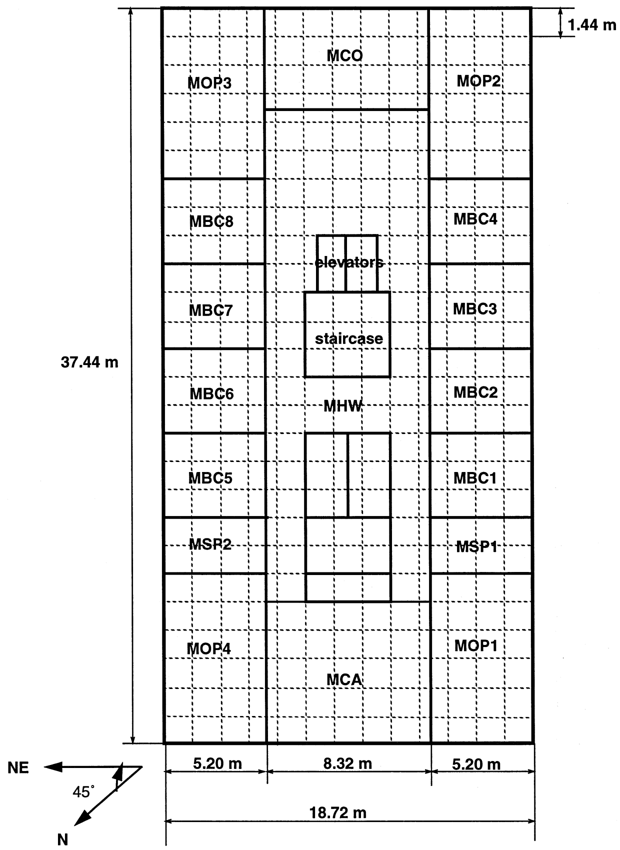


Fig. 1. Basecase building orientation and layout.

When the building is conditioned by the radiant cooling system, the ceiling of the office space is an aluminum panel system, made of 20-cm wide panels with water pipes attached on the plenum-facing side. The panel system delimits a 10-cm plenum.

2.1.1. Loads

A variable occupancy pattern in the range of 1 to 2 persons with a schedule from 8 to 17 h was simulated in the office space during weekdays. No occupancy was simulated during weekends. When present, each person generated 115 W heat, of which 75 W sensible and 40 W latent. Of the sensible heat, half was simulated as convective and half as radiative.

A constant load of 275 W of equipment with a schedule from 8 to 17 h on weekdays was modeled in the room. Half of this load was considered convective and half radiative. No internal load was simulated during the weekend.

An infiltration rate of 0.2 ACH (13.5 m^3/h) was modeled during the time when the ventilation system was switched off and the building was not pressurized.

2.1.2. Radiant cooling system

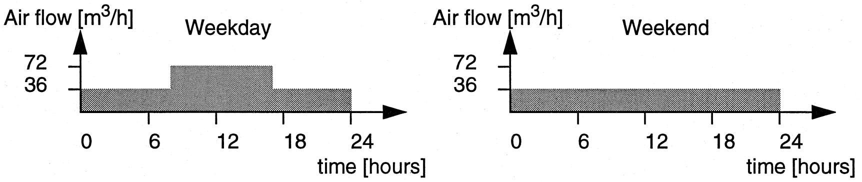
The radiant cooling (RC) system was designed to maintain the indoor air temperature within 1°C of the setpoint temperature of 24°C. To achieve this goal, water was supplied to the radiant cooling panels at a rate of 180 kg/h. To match the loads in different climates, the inlet water temperature was different for different locations. For the purpose of the study, a timer controlled the on/off time of the water flow. On time coincided with occupancy time (8 to 17 h).

Ventilation was provided by a constant volume system functioning with outside air only. The inlet air temperature at all locations was constant at 20°C, and the inlet air humidity ratio was constant at 9.5 g water/kg of dry air (65% relative humidity). To investigate the influence of the presence or absence of moisture buildup due to infiltration at night, two ventilation strategies were simulated (see Fig. 2).

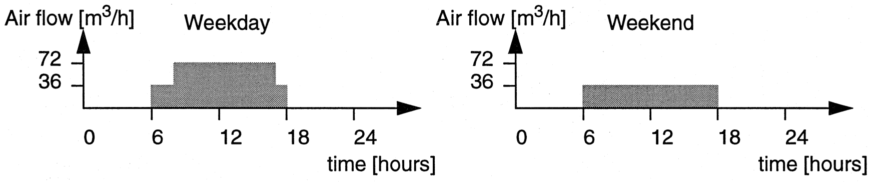
2.1.3. All-air system

A VAV system was modeled to match (1) the outside air volume supplied by the RC system and (2) the indoor air temperature and humidity ratio during occupancy hours. The system sizing was performed separately for each building location to achieve this match.

When the space was continuously ventilated, a CV system replaced the VAV system during the off-occupancy hours. The CV system supplied only outside air at the rate of 36 m^3/h. The supply air was dehumidified to 9.5 g water/kg of dry air.



First ventilation strategy



Second ventilation strategy

Fig. 2. Ventilation strategies: schedules for weekday and weekend hours.

2.2. Building location and simulation periods

To reflect the variability of US climates within the limits of the study, a classification of the available climates was made. Based on this classification, 11 locations were selected. Then at each selected location RADCOOL and DOE-2 calculations were performed for two one-week periods: the week of the VAV system peak power demand and a 'typical week' reflecting the average energy consumption of the all-air system.

2.2.1. Climate classification

The study was designed to estimate the difference in energy consumption and peak power demand of a radiant cooling system and an all-air system providing the same indoor conditions. An ideal climate classification must not bias the result of the comparison in favor of either system.

The following strategy was developed for classifying the 240 US locations for which weather data was available. First, a calculation of the energy necessary to condition the ventilation air was made for all 240 locations, assuming the same design conditions for outside air supply at each location. Next, the 240 locations were classified in nine groups according to (1) the relative importance of dehumidification in the total energy consumption at each location, and (2) the value of the total energy consumption at each location. This classification allowed the groups to contain approximately the same number of locations. Finally, at least one location of each group was selected for the study. In addition, Scottsbluff, NE was selected to ensure the geographic coverage of the whole US territory, and San Jose, CA was selected to ensure that the results obtained from the study be consistent with the author's experience. The groups and selected sites are presented in Table 1.

2.2.2. The concept of 'week of system peak'

After the locations were selected a DOE-2 input file was created to model the operation of the all-air system. Based on the DOE-2 results, the 'week of system peak' power demand was established for each location.

Table 1
Energy consumption for the cooling and dehumidification of ventilation air. Climate classification and locations selected for the study

Dehumidification fraction of the total cooling energy for ventilation	Total cooling energy for ventilation [MJ h/kg]	Group number	Representative site
Dry 0–50%	0–5.7	1	Seattle, WA
	5.7–12.4	2	Salt Lake City, UT
	12.4–54.4	3	Phoenix, AZ, Scottsbluff, NE
Moist 50–67%	0–18.0	4	Boston, MA, San Jose, CA
	18.0–28.2	5	Chicago, IL
	28.2–88.9	6	Fort Worth, TX
	0–22.0	7	New York, NY
Humid 67–100%	22.0–59.7	8	Cape Hatteras, NC
	59.7–114.7	9	New Orleans, LA

The ‘week of system peak’ occurs at the end of July—beginning of August at all locations selected. Although the ‘week of system peak’ is location-specific, the time of peak demand does not vary very much across the climates. The weather during the ‘week of system peak’ is hot and relatively humid in the selected climates.

Considering the limitations of RADCOOL, comparing the radiant cooling system and the all-air system during the ‘week of system peak’ of the all-air system provides useful information for estimating the difference in peak loads of the two systems.

2.2.3. The concept of ‘typical week’

To provide a realistic estimate of the potential for energy savings during the cooling season, the ‘typical week’ was determined for each location. The ‘typical week’ is defined as the week that reflects the average energy consumption of the air-conditioning system over the cooling season. The ‘typical week’ can thus be used as a proxy for the energy consumption of the all-air system over the entire cooling season (for similar work see [6–8]). Comparing the energy consumption of the radiant cooling system and all-air system during the ‘typical week’ provides useful information about the differences in energy consumption of the two systems over the cooling season.

The ‘typical’ week is location-specific. It occurs at the end of May—beginning of June for seven locations, and at the end of August—beginning of September for four locations. This result is intuitively correct, since the weather-induced cooling loads vary a fair amount over the cooling season, and this variability is captured only in the weeks belonging to the ‘transition’ seasons (spring or fall).

3. Results and discussion

3.1. Indoor conditions

This section focuses on the indoor conditions at the New Orleans, LA location. Common sense suggests that operating the radiant cooling system in this hot–humid Louisiana climate should be difficult: reducing the risk of condensation on the cooling surface represents a significant challenge. The section compares the indoor air temperature and relative humidity provided by the simulated radiant cooling and all-air systems and examines the effectiveness with which the night ventilation strategies studied reduce the risk of condensation on the cooling surface. Because the results obtained in the other 10 climates selected for the study are qualitatively similar, discussing the simulated space indoor conditions in all climates would be redundant.

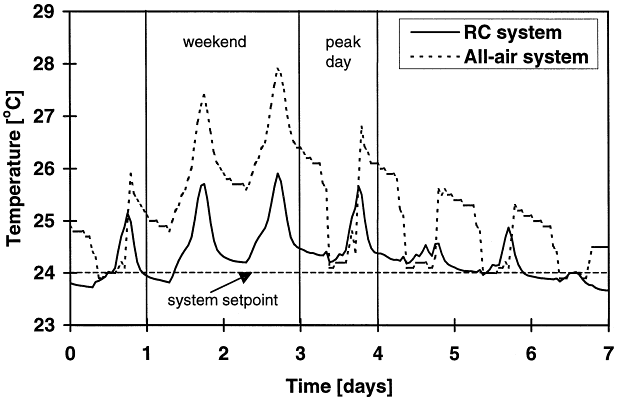


Fig. 3. Indoor air temperature comparison at the New Orleans location during the week of system peak. Space ventilated continuously, half rate at night.

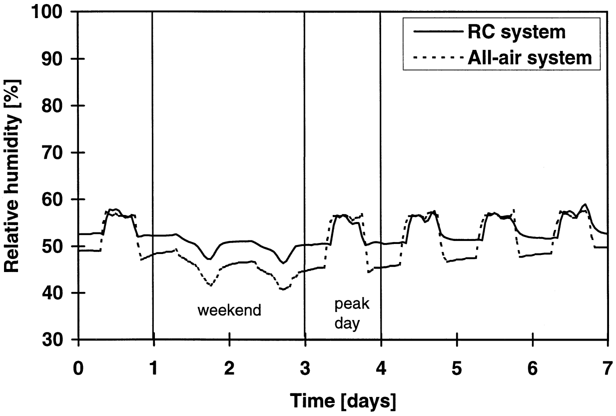


Fig. 4. Indoor air relative humidity comparison at the New Orleans location during the week of system peak. Space ventilated continuously, half rate at night.

During occupancy hours the RC system provides similar indoor air temperature and relative humidity to those provided by the all-air system. Figs. 3–6 show a comparison of the indoor conditions at the New Orleans location. The period covered by the graphs is the ‘week of system peak’ in New Orleans (Friday, July 22 through Thursday, July 28). The second and third days in Figs. 3–6 are weekend days.

Over a 24-h period the RC system provides more stable indoor conditions than the all-air system. The structure of

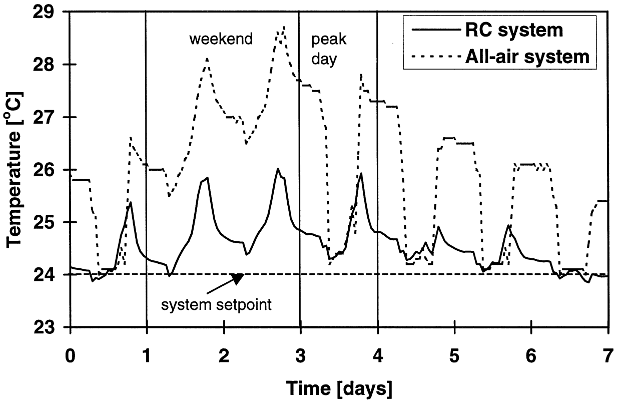


Fig. 5. Indoor air temperature comparison at the New Orleans location during the week of system peak. Space ventilation interrupted at night.

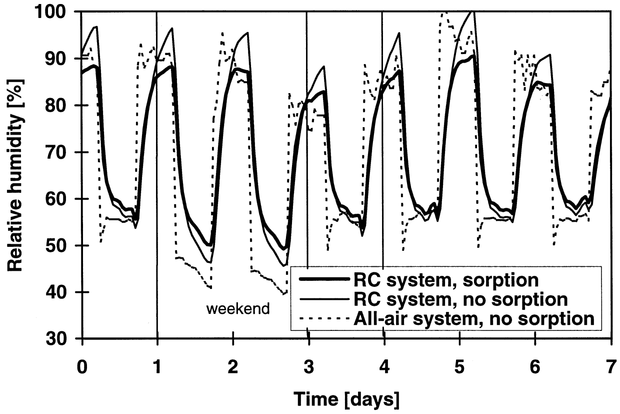


Fig. 6. Indoor air relative humidity comparison at the New Orleans location during the week of system peak. Space ventilation interrupted at night.

the building conditioned by the all-air system stores heat during the day, mainly because the convective heat removal strategy of this system does not cool the structure very efficiently. The structure of the building conditioned with the RC system also stores heat during the day, but not as much because the radiant system actively removes a large part of this heat by means of radiation. As a result, during the off hours the air inside the building conditioned with the all-air system presents a temperature swing of 2.5 to 3°C due to heat release from the walls. The corresponding temperature swing is around 1.5 to 2°C in the building conditioned by the RC system. Should a building occupant decide to work during the off hours period, the building cooled by the RC system would still present comfortable conditions (as defined by ASHRAE Standard 55-1992 [9]), while the building cooled by the all-air system would be too warm.

Continuous space ventilation (and dehumidification) at night provides the benefit of avoiding moisture buildup due to infiltration. If space ventilation is interrupted at night and infiltration with moist air occurs, it is important to account for sorption when performing the mass balance for the indoor humidity level (see Fig. 6). The results of a moisture mass balance accounting for sorption show that condensation does not form the cooling panels when the ventilation is switched off at night, even in this hot humid Louisiana climate. However, if the cooling water temperature were supplied at a lower temperature than the 20°C assumed in these simulations, condensation would form on the surface of the cooling panels.

3.2. Radiant cooling system results

The parameters used in the RADCOOL simulations of the space conditioned by the radiant cooling system, and in the DOE-2 simulations of the space conditioned by the all-air system, allow the calculation of the sensible, latent and distribution loads for each system. This section discusses the results of the calculation performed for the radiant cooling system while Section 3.3 discusses the results for the all-air system.

At 9 of the 11 locations examined, supplying cooling water at 20°C to the ceiling panels allows the radiant cooling system to maintain the indoor air temperature within one degree of the 24°C design setpoint during occupancy hours. If the moisture mass balance accounts for sorption on the walls and floor of the space, the simulation results indicate that condensation does not form on the surface of the ceiling panels at any of the locations studied. This statement holds for the typical week and the week of system peak, and for both ventilation strategies.

The locations where the ceiling panels do not have sufficient cooling power if the cooling water is supplied at 20°C are Phoenix, AZ and Salt Lake City, UT. In these two climates, the daily maximum radiant load exceeds 40 W/m^2, the outside air temperature exceeds 35°C, and the outside relative humidity is 10% on average (during both the typical week and the week of system peak). At these locations the radiant cooling system cannot maintain the ambient temperature near the 24°C setpoint unless the cooling water is supplied at 17.5°C. Because Phoenix and Salt Lake City are dry locations, lowering the supply water temperature does not increase the risk of condensation on the ceiling panels.

Table 2 contains the simulation results for the RC system. The author notes that these calculations assume a constant coefficient of performance (COP) of 3 for the cooling coil-chiller combination serving the radiant system. The ratio of the peak thermal load to the peak electrical load is therefore almost 3 to 1 (the fan contribution to the peak power demand of the RC system is small).

Table 2
Radiant cooling system energy consumption and peak power demand

		Energy consumption [kW h_e/m^2]		Peak power demand [W_e/m^2]	
		Low	High	Low	High
Space continuously ventilated	location	Seattle	New Orleans	Seattle	Cape Hatteras
	modeled period	0.55	1.30	20.5	30.3
	season	14.5	34.3		
Ventilation switched off at night	location	Seattle	Phoenix	Seattle	Cape Hatteras
	modeled period	0.54	1.13	20.9	30.7
	season	14.1	29.7		

Table 3
All-air system energy consumption and peak power demand

		Energy consumption [kW h_e/m^2]		Peak power demand [W_e/m^2]	
		Low	High	Low	High
Space continuously ventilated	location	Seattle	Phoenix	Seattle	Phoenix
	modeled period	0.59	1.92	29.8	45.9
	season	15.4	50.6		
Ventilation switched off at night	location	Seattle	Phoenix	Seattle	Phoenix
	modeled period	0.69	1.95	30.3	48.5
	season	18.3	51.3		

A constant COP of 3 was also considered in the subsequent calculations for the all-air system.

The energy consumption of the radiant cooling system varies across the climates. Because continuous ventilation is associated with longer system operation, the RC system energy consumption during the typical week is larger when the space is continuously ventilated than when space ventilation is interrupted at night.

The peak power demand due to conditioning the space does not vary much across the climates. Because interrupting the ventilation at night is associated with larger building loads to be removed the following day, the peak electrical power demand of the RC system is larger when space ventilation is interrupted at night than when the space is continuously ventilated.

3.3. All-air system results

The all-air system employs a variable air volume system during occupancy hours (8 to 17 h) and a constant volume system, or no system at all, during off-occupancy hours. Table 3 contains the simulation results for the all-air system.

3.4. Comparison of RC system and all-air system

3.4.1. Energy consumption

At all locations examined, the energy consumption of the radiant cooling system was lower than the energy consumption of the all-air system. This statement holds for the typical week as well as for the week of system peak, and for both ventilation strategies. The ‘opportunity for savings’ of the radiant cooling system resides in the fact that removing heat from the space by circulating relatively large volumes of air is more energy-intensive than removing heat from the space by circulating water and ventilation air. In other words, the sensible air cooling and fan energy consumption of the all-air system are higher than the sensible air cooling, sensible water cooling, fan and pump energy consumption of the radiant cooling system.

Table 4 contains the numerical results of the study. At all locations the energy savings achieved when space ventilation is interrupted at night are larger than the energy savings achieved when the space is ventilated continuously. This happens primarily because the all-air system provides an ‘opportunity for savings’ mainly during occupancy hours. Interrupting the space ventilation at night is associated for both systems with additional sensible cooling energy consumption during the next day, and for the all-air system with additional fan energy consumption. This increases the ‘opportunity for energy savings’ when the ventilation is interrupted at night, as compared to the case when the space is continuously ventilated.

The numerical value of the energy savings achieved by replacing the all-air system with the radiant cooling system varies as a function of the building location. The study shows that the savings in cool climates are lower than the savings in hot climates; the savings in hot moist climates are lower than the savings in hot dry climates. This is intuitively correct, considering that the ‘opportunity for

Table 4
Radiant cooling system energy savings potential

		Energy savings		Average	Standard deviation
		Low	High		
Space continuously ventilated	location	Seattle	Phoenix		
	energy savings	0.9 kW h_e/m^2	18.1 kW h_e/m^2	8.9 kW h_e/m^2	4.8 kW h_e/m^2
	% savings[a]	6%	36%	25.4%	9.6%
Ventilation switched off at night	location	Seattle	Phoenix		
	energy savings	4.2 kW h_e/m^2	21.7 kW h_e/m^2	12.1 kW h_e/m^2	4.9 kW h_e/m^2
	% savings[a]	23%	42%	34.8%	6.7%

[a] The fractional energy savings are calculated as energy saved by the radiant cooling system divided by all-air system energy consumption.

savings' is larger at the locations where the sensible energy load is higher. In hot moist climates the dehumidification energy consumption represents a large fraction of the total energy consumption. This leads to a smaller 'opportunity for savings' as compared to hot dry climates.

The author notes that when the space is continuously ventilated, supplying fresh air at a temperature lower than 20°C in dry climates would not lead to condensation on the radiant surface. Consequently, if the radiant cooling system had been designed to take advantage of this opportunity to reduce the system load at night, the calculated energy savings would have been higher than those reported in this section.

3.4.2. Peak power demand

Due to the difference in heat removal mechanisms of the radiant cooling system and all-air system, the two systems reach their peak power demand at different hours during the peak day. The time of peak of the all-air system usually happens shortly after noon. The time of peak of the radiant cooling system usually happens one or two hours later.

In all the climates studied the peak power demand of the radiant cooling system is lower than that of the all-air system. This statement is true for the typical week as well as for the week of system peak, and for both ventilation strategies. It can be explained based on (1) the heat removal mechanisms of the two systems (radiant vs. convective), and (2) the size of the fan employed by each of the two systems at the time of the peak demand (the radiant cooling system employs a much smaller fan than the all-air system).

Table 5 contains the numerical results of the study. The peak power savings do not vary much with the building location. As in the case of the energy savings, the peak power savings are larger when the space ventilation is interrupted at night than when the space is continuously ventilated. This happens primarily because, when space ventilation is interrupted at night, the energy that must be removed during the next day increases, so the peak cooling demand increases for both systems. Because the all-air system cools the space mainly by convection, and because it employs a larger fan than the radiant cooling system, the increase in the peak power demand of the all-air system is larger than the increase in the peak power demand of the radiant cooling system.

3.5. Generalization of the results: energy and peak power saving trends across the climates

To generalize these results, trends were found that allow an estimate of the energy and peak power savings in any climate. The following steps were necessary in establishing these trends.

(1) The appropriate night ventilation strategy (continuous or interrupted night ventilation) was determined for each of the climates studied. This operation was done on the basis of the revised version of ASHRAE Standard 62 [10], which requires the indoor relative humidity to be maintained under 70% at all times. By examining the indoor conditions provided by the two night ventilation strategies, it was found that the indoor air humidity becomes higher than 70% in the humid climates (New Orleans, Cape Hatteras, New York, Fort Worth, and Chicago) if the space ventilation is interrupted at night. Therefore, in these climates the recommended night ventilation strategy is to ventilate the space continuously. By comparison, the indoor relative humidity is always lower than 70% in the drier climates (Boston, San Jose, Phoenix, Scottsbluff, Salt Lake City, and Seattle). Therefore, the recommended night ventilation strategy is to interrupt space ventilation at night.

(2) A first possible representation of the results is that of a distribution of the fractional energy and peak power savings with respect to the number of locations at which the given savings are achieved (see Fig. 7). This representation does not provide the capability to predict the potential savings of a RC system that would replace a given all-air system at a given location. However, this representation shows the potential of the radiant cooling system to substantially decrease energy consumption and peak power demand if used in place of the all-air system.

(3) The behavior of the all-air system is much better known than that of the RC system. Correlations were therefore sought that would link the energy and peak power savings of the RC system to some characteristics of

Table 5
Radiant cooling system peak power demand savings potential

		Peak power savings		Average	Standard deviation
		Low	High		
Space continuously ventilated	location	New York	Phoenix		
	peak savings	7.1 W_e/m^2	16.0 W_e/m^2	10.0 W_e/m^2	2.2 W_e/m^2
	% savings[a]	22%	35%	27.2%	4.0%
Ventilation switched off at night	location	New York	Phoenix		
	peak savings	7.6 W_e/m^2	18.3 W_e/m^2	10.8 W_e/m^2	2.8 W_e/m^2
	% savings[a]	23%	37%	28.4%	4.3%

[a] The fractional peak power savings are calculated as peak power saved by the radiant cooling system divided by all-air system peak power demand.

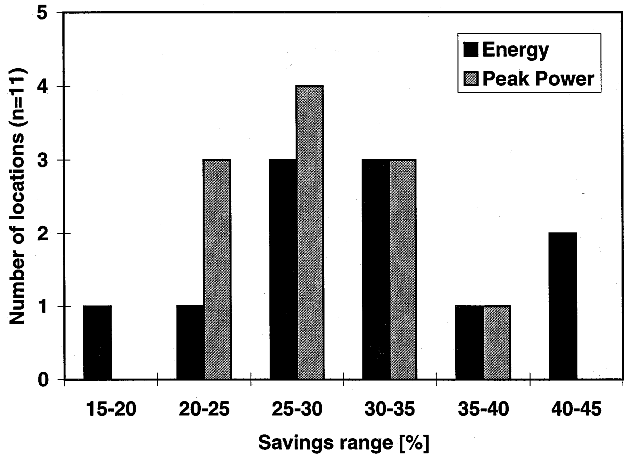


Fig. 7. Distribution of the energy and peak power savings of the radiant cooling system with number of locations. Energy average = 30.5% standard deviation = 7.9%. Peak power average = 27.7%, standard deviation = 4.4%.

the all-air system. Such correlations would then establish the potential savings of a RC system designed to replace a given all-air system.

(4) By design, the simulated radiant cooling system and all-air system cool and dehumidify the same amount of outside air, and provide a similar air relative humidity inside the base-case space. Because the two systems consume the same amount of dehumidification energy, the dehumidification process does not provide any ‘opportunity for savings’ or any energy penalties to the radiant cooling system. Conversely, the sensible load and the fan load due to air distribution of the all-air system offer ‘opportunity for savings’. The savings achieved by the radiant cooling system should therefore correlate with the sensible cooling and fan energy consumption (or peak power demand) of the all-air system.

Fig. 8 presents the energy savings of the radiant cooling system as a function of the sum of the sensible cooling and the fan energy consumption of the all-air system.

The data points and the solid-and-dotted line in the figure correspond to the results reported in the previous section, and assume a COP of 3 for the cooling coil-chiller combinations serving the two systems. The dashed lines in Fig. 8 correspond to similar calculations of the all-air system and radiant cooling system energy consumption, performed with the assumption that the cooling coil-chiller combinations serving both systems have COP values of 2.5 and 6, respectively.

The linear regression between the two quantities indicates that the radiant cooling system can achieve high energy savings at the locations where the sum of the sensible and fan energy consumption of the all-air system is high. An examination of the locations associated with the data points in Fig. 8 shows that the absolute energy savings are highest in the hot climates and lowest in the cold climates, regardless of the dehumidification energy consumption.

For the climates in the study the energy savings over the cooling season varied between 4.1 kW h_e/m^2 (Seattle) and 21.7 kW h_e/m^2 (Phoenix), with an average of 10.6 kW h_e/m^2 and a standard deviation of 5.0 kW h_e/m^2. The energy savings in the hot humid climates were close to the average. Considering a flat rate of US\$0.11/kW h_e for the electric energy, the average energy savings translate into savings of US\$1.1/m^2 in cooling electricity bills. This represents about 10% of the total electricity bill of the typical office space in the US.

The regression line for COP = 3 shows that, at locations where the sum of the seasonal sensible cooling and fan energy consumption of the all-air system is lower than 10 kW h_e/m^2, replacing the all-air system with a radiant cooling system will not save energy. The 10 kW h_e/m^2 value can be interpreted as the sensible cooling and fan energy consumption associated with supplying only the ventilation air to the space. Among the locations examined, Seattle presents the lowest sum of the seasonal sensible cooling and fan energy consumption of the all-air system: 18.1 kW h_e/m^2.

The regression line corresponding to COP = 2.5 has a slightly lower slope than the slope of the regression line for COP = 3, while the regression line corresponding to COP = 6 has a slightly higher slope. Consequently, using a chiller that consumes less electrical energy to achieve the same thermal cooling at the coil increases the fraction of the sensible cooling and fan energy that can be saved by replacing the simulated all-air system with the simulated radiant cooling system. The author notes that in Fig. 8, the ‘closeness’ of the regression lines corresponding to different COP values is due to the assumptions embedded in the parametric study. Although it is difficult to estimate the applicability of these results in other situations, the existence of a linear relationship between the savings achieved by the radiant cooling system and the ‘opportunity for

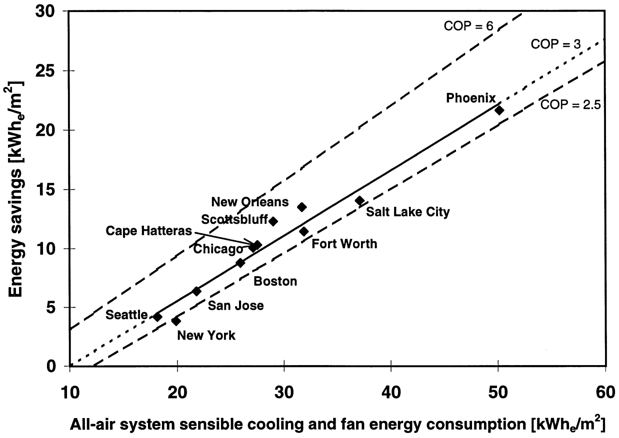


Fig. 8. Energy savings over the cooling season: trend across climates.

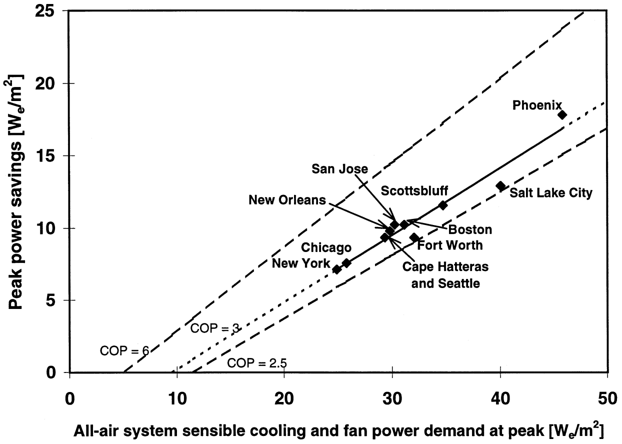


Fig. 9. Peak power savings: trend across climates.

savings' offered by the all-air system is an important result.

Fig. 9 presents the peak power savings of the simulated radiant cooling system as a function of the sum of the sensible cooling and fan power demand of the simulated all-air system at the time when it reaches its peak demand. The two quantities correlate linearly, indicating that the radiant cooling system can achieve high peak power savings at the locations where the sum of the sensible cooling and fan power demand at the time of the all-air system peak is high.

The data in Fig. 9 show that the absolute peak power savings are highest in the hot, dry climates, and lowest in the cold humid climates. Furthermore, the absolute peak power savings are relatively high in all dry climates and relatively low in all moist climates. This is intuitively correct, because the 'opportunity for savings' at the time of the all-air system peak power demand is high in hot climates, and is low in moist climates.

The peak power savings increase with an increase of chiller COP. The regression line for $\mathrm{COP} = 3$ suggests that, if the sum of the cooling and fan power demand of the all-air system at the time of peak is less than 8 W_e/m^2, replacing the all-air system with the radiant cooling system will not save any peak power demand. This value designates the peak sensible cooling and fan load associated with supplying only the fresh air volume to the space.

For the climates in the study the peak power savings varied between 7.1 W_e/m^2 (New York) and 17.8 W_e/m^2 (Phoenix) with an average of 10.3 W_e/m^2 and a standard deviation of 2.8 W_e/m^2. The peak power savings in hot humid climates were close to the average.

4. Additional modeling

The results discussed above are important in a situation where the designers of a new office building structure are interested in installing an 'alternative' (to the typical all-air) building conditioning system. However, the following limitations should be considered before using the above results to make a decision about installing a radiant cooling system in a building. First, the results were obtained by comparing the performance of a simulated radiant cooling system with that of a simulated all-air system that conditions the same specific single-zone office space. It is not certain that the results obtained for the base-case space selected for the study can be used to calculate the savings potential of a radiant cooling system with a different design, conditioning a different space, or a whole building. However, the author notes that the integration of RADCOOL into DOE-2 would allow building practitioners to perform simulations for a the building structure of their choice, and to evaluate the savings potential of a radiant cooling system of specified design, as compared to an all-air system of specified design. Second, these results were obtained for an office space with a state-of-the-art envelope complying with current California standards. But the number of new office buildings that will be built in the future is relatively small compared to the number of older office buildings that will be retrofitted. If radiant cooling achieves significant market penetration in the US, radiant cooling systems are more likely to be installed during a retrofit than during the construction of a new structure. It would be interesting to know whether the results obtained for the base-case space in the state-of-the-art structure can be used to draw conclusions about the savings potential of a radiant cooling system in a different building structure.

To extend the building domain where the results obtained in this thesis are applicable, additional modeling is necessary. The following will present the results of a few additional simulations. This work explores the extent to which the correlations obtained for the base-case space may change when the energy and peak power savings of the simulated radiant cooling system are calculated for a different space in the building, and for a different building structure.

4.1. Description of the additional simulations

To partially address the first concern stated above, additional modeling was performed to evaluate the energy and peak power savings potential of a RC system providing the same indoor conditions as an all-air system in a different basecase office space. The space MBC6 was chosen for this purpose (Fig. 1, orientation 45° east of north). Similar simulations as those for the space MBC2 were performed for two locations: New Orleans, with the space continuously ventilated and Phoenix with the space ventilation interrupted at night.

To partially address the second concern stated above, additional modeling was performed to evaluate the energy and peak power savings potential of a RC system in a different building structure. The building structure chosen for this purpose is representative of the 'old' building stock dating from the 1950s. The facade consists of metal panels, insulation and sheetrock, with the opaque part having a U-value of 1.74 W/m^2 K and single-pane windows with a center-of-glass U-value of 5.58 W/m^2 K. Similar simulations to those for the 'new' building structure were performed for the MBC2 space at two locations: New Orleans, with the space continuously ventilated and Phoenix, with the space ventilation interrupted at night.

It is important to note that, for consistency with the previous work, the simulation of the space with the 'older' building structure was made assuming (1) the same (relatively low) internal loads as those in the parametric study, and (2) the possibility of avoiding infiltration at the New Orleans location by pressurizing the space. Depending on the building to be retrofitted, one or both of these assumptions may not hold. High internal loads at hot dry locations might indicate that radiant cooling systems do not have enough cooling power to condition certain retrofitted buildings. High infiltration rates and high internal loads at hot humid locations might indicate a relatively high risk of condensation in certain buildings, even if continuous ventilation is employed. In such extreme conditions, the decision to install a radiant cooling system must be based on simulations for each retrofitted building. The building practitioner must then make a decision based on (1) the lowest acceptable energy savings of the radiant cooling system as compared to an all-air system, and (2) the highest acceptable risk of condensation.

4.2. Discussion of the results

The data points for the energy and peak power savings in the additional situations (different orientation of the space and different building structure) are presented in Figs. 10 and 11. These figures also contain the trend graphs from Figs. 8 and 9, and the data points for the energy and peak power savings in the base-case situation ('new' structure, SW orientation of the space).

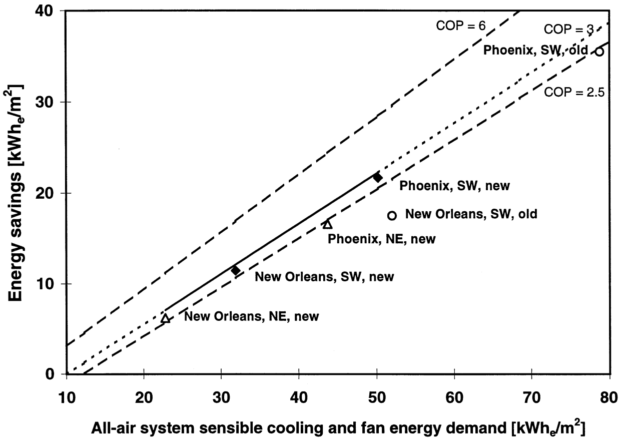


Fig. 10. Energy savings over the cooling season: data for New Orleans and Phoenix.

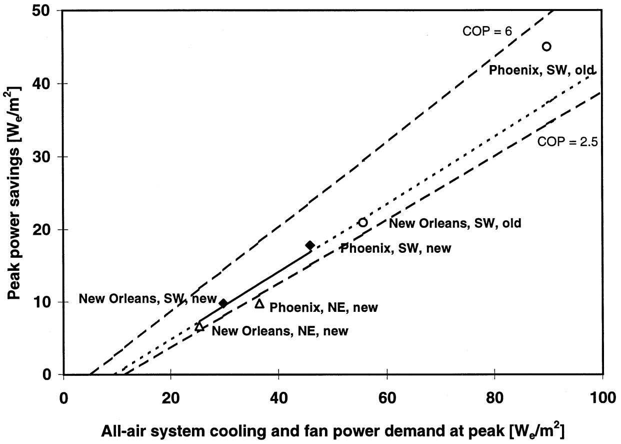


Fig. 11. Peak power savings: data for New Orleans and Phoenix.

When evaluating the position of the new points on the trend graphs it is important to remember that the RC system has more 'opportunity for savings' when (1) the sensible cooling load is large, and (2) the corresponding all-air system employs a large fan.

The solar heat gain through the window of an office space oriented with the exterior wall facing north-east occurs mainly in the morning. At the time of the maximum solar heat gain (9 AM), the building structure has not had a chance to warm up just yet. By comparison, the maximum solar heat gain occurs at 3 PM in the office space oriented with the exterior wall facing south-west. At this time the building structure is already warm, therefore it cannot store part of the cooling load. When compared to the space facing SW, a system conditioning the space facing NE will experience a smaller weather-induced heat gain. The opportunity for savings is thus lower in the NE-oriented space than in the SW-oriented space. Figs. 10 and 11 confirm this observation.

The solar gain through a poorly insulated structure is larger than the solar gain through a well insulated structure. The results of modeling the 'old' structure confirms this observation (Figs. 10 and 11). Because the ventilation air supplied to the building is the same as in the case of the 'new' building structure, the higher potential savings of the RC system in the case of the 'old' building structure are solely due to the low insulation level of the 'old' building.

It is important to note that, although the results reported in this paper reflect the specific assumptions embedded in the parametric study (occupant and equipment schedules, design and operation of the all-air and radiant systems, the method of matching the indoor conditions of the space, etc.), they confirm that substantial energy and power savings can be achieved by substituting radiation for convection as a heat transfer mechanism, and water for air as the heat transfer medium. Once RADCOOL integration into

DOE-2 is achieved, building practitioners will be able to perform similar studies using assumptions appropriate to their specific buildings.

5. Conclusions

(1) Different ventilation strategies are necessary at different locations to ensure that office building conditions comply with the upcoming building regulation (at least with the revised version of ASHRAE Standard 62-1989 [10]). The design of the ventilation strategy and the design parameters of the building conditioning system should therefore reflect local climate characteristics. Specifically, the indoor relative humidity of office buildings located in moist climates should be controlled through continuous ventilation with dehumidified air. Because humidity buildup does not constitute a problem in climates where the outside dew point temperature is lower than the panel surface temperature (generally, in dry climates), moisture control through night ventilation is not necessary in these climates.

(2) An adequately designed and operated radiant cooling system can function in a state-of-the art office building at any US location with low risk of condensation. In humid climates, the risk of condensation on the radiant surface is greatly reduced if the building is continuously ventilated with dehumidified outside air. However, continuous ventilation may fail to lower the risk of condensation to acceptable levels in leaky buildings of older vintage.

(3) Over a 24-h period, the simulated indoor air temperature in the base-case space conditioned by the radiant cooling system is more stable than the simulated indoor air temperature in the base-case space conditioned with the all-air system.

(4) The simulated radiant cooling system requires less energy and peak power to condition the base-case space than the simulated all-air system. At the locations studied, and in a state-of-the-art office space conditioned to meet the requirements of ASHRAE Standard 62R, the average savings potential of the simulated radiant cooling system is 30% for the energy consumption, and 27% for the peak power demand. If radiant cooling systems can remove the higher cooling load characteristic for buildings of older vintage, higher savings are achievable in these lighter structures.

(5) The potential savings of the simulated radiant cooling system are lower in cold, moist climates and higher in hot, dry climates. At the locations studied, the achievable energy savings of the system conditioning the base-case space vary between 17% and 42%. The achievable peak power savings vary between 22% and 37%.

(6) The estimated energy and peak power savings increase when the COP of the cooling coil-chiller combination serving the air-conditioning system increases.

(7) If the sum of the seasonal sensible cooling and fan energy consumption of the all-air system drops below the level at which ventilation air is sufficient for cooling and dehumidification, the ‘opportunity for energy savings’ disappears. Replacing the all-air system with a radiant cooling system will not reduce energy consumption. A similar statement can be made for the peak power demand.

(8) Additional modeling is necessary to clarify to what extent the results presented in this paper are applicable to other building structures and to other orientations. In particular, since retrofit projects will account for a large share of the construction projects in the near future, the savings potential of radiant cooling systems in retrofit projects should be studied in detail. Installing a radiant cooling system in retrofit projects should be preceded by simulations reflecting the conditions for each retrofit situation. RADCOOL integration into DOE-2 would provide building practitioners with a simulation tool capable of evaluating the performance of radiant cooling systems in any specific building and for any specific climate.

(9) Because many other alternative cooling technologies are viable in hot, dry climates (e.g., cooling towers, evaporative cooling, night ventilation), it is recommended that pilot-projects demonstrating the performance of radiant cooling systems be implemented in the warm and hot humid climates first. Installing a radiant cooling system instead of an all-air system in new building construction in these climates can reduce the energy consumption and peak power demand due to air-conditioning by an estimated 25%. Of the existing commercial building stock, about 23% is located in warm and hot humid climates [11].

Acknowledgements

I thank Helmut Feustel for his long-term advice and support. I thank Gene Rochlin, Bill Nazaroff, Cris Benton, and anonymous reviewers for their comments and suggestions on earlier versions of this paper. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

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