APPLICATION OF RADIANT COOLING IN DIFFERENT CLIMATES: ASSESSMENT OF OFFICE BUILDINGS THROUGH SIMULATION

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ABSTRACT

The energy performance of radiant slab cooling relative to conventional air systems to be clarified for climates from cold and dry to very hot and humid. EnergyPlus simulations were used to compare the energy performance of 1) radiant slab cooling combined with a dedicated outdoor air system and 2) a variable air volume system. Simulation results show that the radiant slab system provided 10% to 40% better energy performance depending on the climate type. Key features contributing to better performance were heat recovery on the reduced fan energy use, outdoor air system and water-side economizer free cooling. The best performance was in dry climates. System configurations and operating approaches for radiant slab cooling must be modified on a climate-specific basis to prevent condensation and improve energy performance. In a cold-dry climate, radiant cooling with water-side economizer may allow elimination of compressor-driven refrigeration. In a hot-humid climate, continuous operation of the outdoor air system is required to prevent condensation.

INTRODUCTION

Buildings account for roughly one third of global non-renewable energy use. Space cooling through air-conditioning is typically provided through electric compressor-driven refrigeration, contributing a significant portion of commercial building energy use with direct and indirect negative environmental impacts.

As an alternative to conventional air-conditioning, radiant cooling has the potential to improve building energy efficiency and thermal comfort. While several radiant cooling installations may be found in Western European countries such as Germany and Switzerland (Behne 1999; De Carli and Olesen 2002), it is less common in other countries. One of the reasons is lack of certainty on the part of designers regarding energy performance in different climates.

Several researchers (Handel *et al.* 1992; Brunk 1993; Niu *et al.* 1995; Stetiu 1995; Sodec 1999; Strand 2003) studied have comparing the energy performance of radiant cooling panel systems to that of conventional variable air volume (VAV) systems. Simulation results indicate that the combined radiant panel cooling and ventilation system may, or may not, provide better energy performance. Besides climate conditions, supply air temperature, outdoor flow rates and cooling loads also affect energy performance. Limitations of these studies restrict their broader application.

Firstly, the simulation studies mentioned above (except for Handel *et al*. 1992) were based on one-zone models. Although one-zone model studies are useful, applicability of findings to complex multi-zone building buildings is uncertain. Judikoff *et al*. (2008) concluded from a literature review “few investigators have confidence in the extrapolation from single- to multi-zone predictions.” In large office buildings, extensive core zone spaces require year-round cooling. In shoulder and winter seasons, a conventional VAV system may exploit air-side free cooling (economizer cycle) to meet or partially meet cooling requirements, especially in mild, cool and cold climates. Dedicated outdoor air systems (100% outdoor air systems with air flow rates meet ventilation requirements) as typically used with radiant cooling as well as with fan coil and heat pump systems (the so called water-air systems) have a much more limited free cooling capability compared with all-air systems. This may preclude broader use of simulation results from one-zone models for multi-zone real buildings.

While air-side free cooling opportunities are typically more limited with radiant systems, it has advantages in terms of water-side free cooling using cooling towers and other low exergy systems. Only Niu *et al.* (1995) of the above-mentioned authors considered water-side free cooling in combination with radiant thermal control. As water-side free cooling is considered to offer improved energy-efficiency (ASHRAE 2006; CIBSE 1998), applicability to multi-zone buildings with radiant cooling should be assessed.

Another important issue is the performance of radiant cooling in different climate conditions. Stetiu (1995) used a one-zone model to compare the energy performance of radiant cooling and conventional VAV systems for a typical summer week across a range of climates within the United States. He found that radiant cooling provided cooling energy use reductions of 17% to 42% relative to the conventional VAV system. However, a year-round multi-zone assessment would be more informative for designers. Further, Stetiu's simulations (1995, 1999) used two different simulation programs: 1) *DOE-2* for the conventional VAV systems and 2) *RADCOOL* for radiant cooling with dedicated outdoor air. In addition, water-side free cooling was beyond the scope of Stetiu's study.

To complement the research undertaken to date, year-round comparative energy performance of conventional air-based and radiant cooling was conducted for a large multi-zone building. The water-side economizer cycle for radiant cooling was addressed.

METHODS

Both conventional air-based and radiant cooling systems were simulated with *EnergyPlus* program (Version 2.0) (DOE 2007). A typical floor of the tower (levels 3 to 7) of the Information and Communications Technology (ICT) Building at the University of Calgary, Canada was used for the analysis (Figures 1 and 2). The ICT Building has a radiant slab cooling system in the floor slabs of levels 2 through 7. The north and south service zones were excluded from the study, as they lack radiant cooling. The resulting floor area was about 1540 m^2. Calibrated simulation was previously used to identify design and operation changes to improve energy performance in the cold-dry climate (Tian and Love 2009).

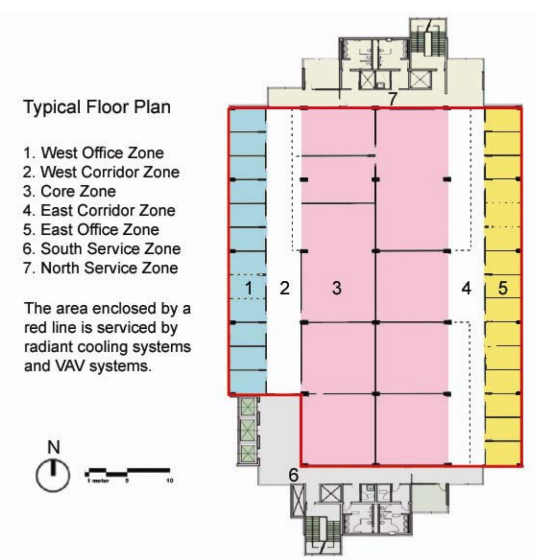

Figure 1 Typical floor plan, levels 3 to 7

To compare energy peformance across a range of climates, it was preferable to modify the building envelope design to suit climate conditions. For example, ASHRAE-IESNA Standard 90.1 (ASHRAE 2004) prescribes of roofs, walls and fenestration for eight basic climate zones. However, applying the ASHRAE 90.1-2004 minimum envelope requirements may fall short of requirements for application of radiant cooling.

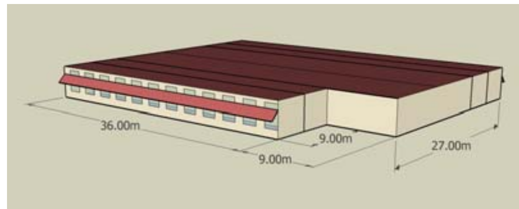

Figure 2 Typical floor of revised design proposed (the area enclosed in the red line in Figure 1)

Radiant thermal control systems have cooling capacities that are typically lower than those of air-based systems (Olesen 1997; Olsesen *et al*. 2003). Use of radiant cooling requires a building envelope design that limits heat gains and lossses to a greater extent than conventional air-based systems (Tian and Love 2009): opaque envelope areas must be well-insulated and glazing especially solar radiation through glazing. In addition, with reduced cooling load, the required chilled (or cooled) water temperature in radiant cooling systems can be increased, which may allow use of low-quality cooling resources. In this study, the same building envelope thermal properties were used in the simulation models to reduce external heat gain to some extent which is within the cooling capapcity of radiant cooling systems.

In the *EnergyPlus* building energy model, the building envelope basic thermal properties were as follows:

- east and west exterior wall effective U-value: 0.3 $W/m^2.K$, compared with the ASHRAE 90.1-2004 baseline value of 0.365 $W/m^2.K$ for a steel-framed wall system in climate zone 7;
- adiabatic south and north exterior wall (as noted above,the north and south service zones were excluded from the study, as they lack radiant cooling);
- exterior window U-value: 1.8 $W/m^2.K$ (a double-glazed window with nonmetallic spacer, emssivity of about 0.03 and gas fill), compared with the ASHRAE 90.1-2004 baseline value of 3.2 $W/m^2.K$ for 30 to 40 percent window-to-wall ratio in climate zone 7;
- glazing solar heat gain coefficient (SHGC) 0.55 compared with the ASHRAE 90.1-

2004 baseline value of 0.49 for 30 to 40 percent window-to-wall ratio on non-north exposures in climate zone 7);

- window-to-wall ratio (east and west walls) 0.4;
- 1 m wide shading devices on east and west walls, 45^o tilt (for control of solar gains as per Love and Tian 2009);
- adiabatic roof and floor surfaces to represent a typical floor of the tower;
- perimeter zone air iniltration rate: 0.21 air changes per hour (ACH), based on infiltration rate of 0.25 L/s per m^2 exterior wall area (NRC. 1997).
- no air infiltration for core zones.

The area-weighted (60% walls, 40% windows) average U-value for the case study design walls and windows is 0.9 W/m^2.K compared with 1.4 W/m^2.K for the baseline value. This combination would also reduce the likelihood of condensation on window in cold weather.

The internal heat gain conditions in the EnergyPlus models were set as follows:

- internal lighting power density: 10.5 W/m^2, slightly better than the ASHRAE 90.1-2004 baseline value of 11 W/m^2;
- electrical equipment power density: 9.5 W/m^2, slightly higher than the 7.5 W/m^2 reported in the literature as typical (Komor 1997);
- occupancy density: 5 people/100 m^2 the default performance path value for offices (NRC. 1997).

The building system parameters such as fan pressure drop and pump head were obtained from the ICT Building design data, representing the real operating conditions.

The fan and pump total static pressure properties are listed as follows:

- supply fan: 996 Pa;
- return fan: 335 Pa;
- hot water circulation pump: 129 kPa;
- chilled water circulation pump: 75 kPa;
- condenser water circulaiton pump: 100 kPa;
- radiant slab cooling pump: 126 kPa.

The combined radiant cooling-dedicated outdoor air (RC+CV) system model included an exhaust air heat recovery unit (sensible effectiveness 0.76) and water-side economizer to provide free cooling through cooling towers when the outdoor temperature conditions allowed. The VAV model had the same building envelope and minimum outdoor air flow (10 L/s per person) as the radiant cooling model. Air-side free cooling was enabled. Exhuast air heat recovery and water-side free cooling were not modeled in the VAV sytems, because VAV systems blended return air reduces the effectiveness of heat recovery, and air-side free cooling is more effective used for the VAV option (all-air system). Auto sizing of equipment, system and plant was used in generating the VAV simulation model, with fan and pump head set to those in the radiant cooling model. It should be noted that when the air system type was changed from VAV to CV, the required supply fan total static pressure should decrease with elimination of VAV boxes. Adding heat recovery would increase the required total static pressure for the dedicated air system, thus the same fan total static presures was used for both. The fan and pump total static pressure properties (except condenser water pump) were obtained from ICT Building construction documents. Figures 3 and 4 illustrated the combined radaint cooling-dedicated ourdoor system and the conventional VAV system air side and water side schematics.

ASHRAE 90.1 (ASHRAE 2004) identifies eight basic climate zones. This comparison was divided into three categories to evaluate the impact of outdoor temperature: 1) cool to very cold climates, 2) mixed and warm climates, and 3) hot and very hot climates. To further clarify the impact of relative humidity, each category was divided into three sub-categories (dry, marine and humid).

Similar to air-based systems for thermal control, radiant panel systems can be shut off during unoccupied hours. Unlike radiant cooling panel systems, However, radiant slab systems will continue to affect the indoor thermal environment for a few hours, even though water flow through the systems is shut off, due to the thermal mass of concrete slabs.

Therefore, two operation schedules were considered: 1) continuous operation for the VAV system and the combined RC-CV system, this is the scenario in the ICT Building and in other similar office buildings with long operation schedule; and 2) with night shutdown of fan systems (in all cases for the VAV system, only where permitted by humidity conditions for the radiant slab system). This is more typical operating schedule for office buildings. For the night shutdown scenario, the following schedule were used:

1) for the conventional VAV system, the air system runs from 07:00 to 22:00 per day;
2) for the RC+CV system, the outdoor air system runs at least from 07:00 to 22:00 per day and continuously if required to control condensation, the radiant slab cooling system ran continuously.

COMPARISON RESULTS

Continuous operation - cold and cool climates

As energy use for cooling is likely to be small in sub-arctic (ASHRAE climate zone 8) climates, the comparison was limited to very cold, cold and cool climates (ASHRAE zones 7, 6A, 6B, 5A, 5B, and 5C). Sample cities were selected for simulation comparison. These cities are listed in Table 1.

The simulated energy uses related to HVAC are listed in Table 1 (fan energy includes supply fan, return fan and cooling tower fan; pump energy includes pumps for hot water, chilled water and condenser water). The simulated building energy use with the RC+CV system was always lower than with the conventional VAV system. The biggest energy use reduction was for fans. In the RC+CV system, the cooling energy use is related to both outdoor dry-bulb temperature and relative humidity. In the respective very cold-dry and cool-marine climates of Calgary and Vancouver, the depression of wet-bulb temperature is below dry-bulb temperature allows extensive use of water-side free cooling. In humid climates represented by Toronto and Portland, much of the time the chilled water temperature has to be decreased below that possible with a cooling tower to dehumidify supply air to prevent condensation, thus the possibility for saving from cooling has been reduced. As may be seen from Table 1, cooling energy use for the RC+CV and conventional VAV systems is similar.

Continuous operation - mixed and warm climates

Representative cities in mixed (Zones 4A, 4B, 4C) and warm climates (Zones 3A, 3B and 3C) are listed in Table 2.

The simulation results (Table 2) reveal that even in the mixed-dry and mixed-marine climatic zones such as Albuquerque and Seattle, radiant slab cooling systems allow substantial cooling without chillers. This is due to the large difference between dry-bulb and wet-bulb temperatures in the dry and marine climates. However, in warm climates such as El Paso and Los Angeles, as the outdoor air temperatures increase in warm weather, cooling towers cannot provide cooled water temperatures low enough to meet the cooling requirement and chillers may be required. For the RC+CV system, pump energy use increases due to the long operation hours of condenser loop and is close to fan energy use.

Continuous operation - hot climates

The sample cities in hot and very hot climatic zones are listed in Table 3. In hot and humid climates as represented by Houston and Miami, due to the high relative humidity, chilled water temperatures of 6-8 ^{o}C are required in the warm and hot weather conditions to dehumidify supply air sufficiently to prevent condensation with radiant slab cooling.

The results (Table 3) reveal that even in hot-humid climates such as those of Houston and Miami, radiant cooling system may still be applicable in building types such as offices. The key issue is control of indoor relative humidity by dehumidification of supply air and reduction of infiltration. Operable windows with appropriate control is required when combined with radiant slab cooling .

Night-time shutdown of air supply

Four climates zones: zone 6A, zone 6B, zone 2A and 2B were selected for evaluation. The simulation results (Table 4) show that in humid climates such as those of Toronto and Houston, when the outdoor air system was scheduled off during off-occupancy hours, condensation may occur with radiant slab cooling in the warm months. Therefore, this operating schedule should be avoided for combined radiant slab cooling and air systems in humid climates and the ventilation system should operate continuously. In Toronto's cold-humid climate, cooling energy use in the RC+CV system is close to that in a conventional VAV system with the ventilation fan shut down overnight. The energy use reduction with the RC+CV system is around 16% compared with the conventional VAV system. In the cold-dry climate like Helena, the RC+CV system has the energy use reduction of around 40% compared to the conventional VAV system. In Houston's hot-humid climate, the RC+CV system provides a reduction of about 22% compared with the conventional VAV system, while in the hot-dry climate like Phoenix the reduction is around 36%. Among all four climates, the absolute energy use reduction is the highest in the hot-dry climate.

Overview of results

The largest energy use reductions with radiant cooling system occurred in the dry climates, where chillers may be unnecessary. Elimination of chillers also provides an offset to the first cost of the slab piping. The smallest energy use reduction was in the cold-humid climate because 1) the conventional VAV system allowed extensive use of air-side free cooling with low outdoor temperatures and 2) cooling energy use is relatively small compared with that in warm or hot climates. Radiant slab cooling provided better energy performance in dry climates than humid climates because 1) less energy is required to dehumidify supply air and 2) low-quality sources such as evaporative systems can provide adequate cooling in dry climates. Only the first of these two factors was identified by Stetiu (1999), who indicated the savings for radiant cooling compared with conventional VAV system in cool climates were lower than the savings in hot climates. When water-side economizer was excluded in the simulation, the combined RC+CV system may have more energy use than the conventional VAV system in cold climate (Tian and Love 2009). The RC+CV system percent energy use reduction for Helena (cold-dry) was greater than that for Houston (hot-humid) when water-side free cooling was exploited. The absolute reductions were similar. Although this paper and Stetiu's paper (1999) show similar reduction for the combined RC+CV system compared with conventional VAV system (around 10-40%), it should be noted that the results are based on different conditions: 1) one year simulation compared with one typical summer week, 2) one building model compared with one zone model, and 3) with and without water-side free cooling.

CONCLUSIONS

EnergyPlus simulations were used to evaluate the energy performance of radiant slab cooling combined with a dedicated outdoor air system (RC+CV). A typical floor of a large office building (separated core and perimeter spaces) was modeled with 1) an RC+CV system and 2) a conventional VAV system. Results for a range of climates show that radiant slab cooling with dedicated outdoor air systems provided better energy performance than the conventional VAV system in all 16 climate zones. The energy improvements are due to four main factors:

1) with reduced air flow, fan energy use was reduced; the increased pump energy use to operate the chilled slab was less than fan energy savings;
2) radiant cooling allowed more extensive use of low-quality cooling sources such as cooling towers, dry coolers and ground water sources;
3) with higher chilled water temperatures in radiant slab cooling, the chiller efficiency increased;
4) heat recovery system reduced energy use for heating and precooling of outdoor air.

The simulation results also indicate that radiant slab cooling can be applied in office buildings in a wide range of climates, including hot-humid regions where radiant cooling systems has typically been considered unsuited. However, use of radiant slab cooling in hot-humid climates requires some special measures.

1) The supply air requires dehumidification to prevent condensation. The chilled water supplied to the cooling coils must be reduced to about 6 ^{o}C to dehumidify supply air or desiccant cooling equipment may be applied.
2) The building envelope must be very air-tight. The infiltration rate through building envelope has to be kept low. Natural ventilation without combined control is problematic for radiant slab cooling in humid climates due to condensation risk.
3) Heat gains through the building envelope, especially gains due to solar radiation through glazing, must be kept low so that the temperature of chilled water supplied to the radiant slab can be increased, which reduces the possibility of condensation.
4) In humid climates, ventilation fans may have to run more hours in the combined RC+CV system than that in the conventional VAV system to prevent condensation problems.

This study shows that the energy performance of radiant cooling is closely related to the humidity conditions as well as to outdoor temperature. For instance, radiant cooling-dedicated outdoor air systems could provide greater energy use reductions in hot-dry climates than in cold-humid climates. Radiant cooling with dedicated outdoor air system may have better performance than conventional VAV systems in hot-humid climates than in cold-humid climates. The combined radiant cooling-dedicated ventilation system provided better energy performance in dry and marine climates than in humid climates.

It should be noted that all simulation results discussed in this study are based on the same building envelope construction to facilitate comparison of results. Climate-responsive design and variation in building energy codes and standards would lead to variations across climate zones. Building and HVAC design is not "one design fits all". In dry areas, fluid coolers may be more suitable than cooling towers. Future research should consider the VAV and radiant cooling design alternatives for specific climate zones with designs tailored to those climate zones. U.S. Department of Energy (DOE 2009) recently released benchmark energy models for commercial buildings based on ASHRAE 90.1-2004. These models can be used in further studies of the energy performance of radiant cooling in different climates.

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Table 1 Simulated HVAC energy uses in cold and cool climates (continuous operation)

Climate Zone		Zone 7	Zone 6A	Zone 6B	Zone 5A	Zone 5B	Zone 5C
Generic Description		Very Cold	Cold-Humid	Cold-Dry	Cool-Humid	Cool-Dry	Cool-Marine
City		Calgary, AB	Toronto, ON	Helena, MT	Portland, ME	Salt Lake City, UT	Vancouver, BC
VAV Energy Use (GJ)	Cooling	25	55	39	53	69	22
	Heating	160	146	130	139	89	88
	Fan	112	123	126	118	154	99
	Pump	10	15	11	13	13	11
	Total	307	339	307	323	325	219
RC+CV Energy Use (GJ)	Cooling	0	48	0	58	0	0
	Heating	105	97	82	92	50	60
	Fan	64	69	67	70	74	67
	Pump	32	55	38	51	42	29
	Total	201	269	187	271	166	156
	Savings	35%	21%	39%	16%	49%	29%

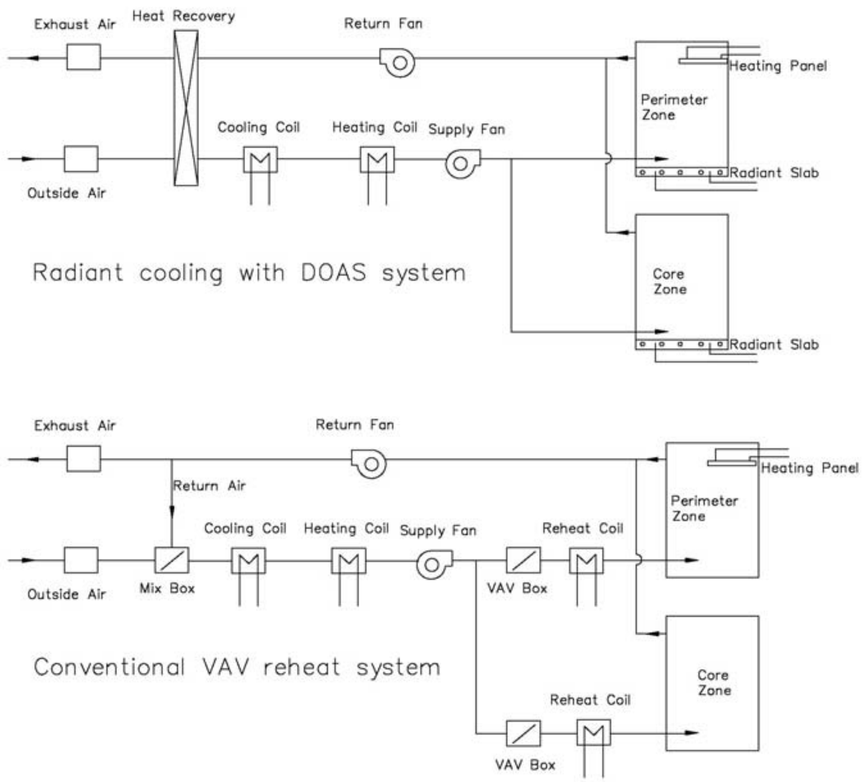

Figure 3 Radiant cooling with DOAS system and VAV system configurations (air side)

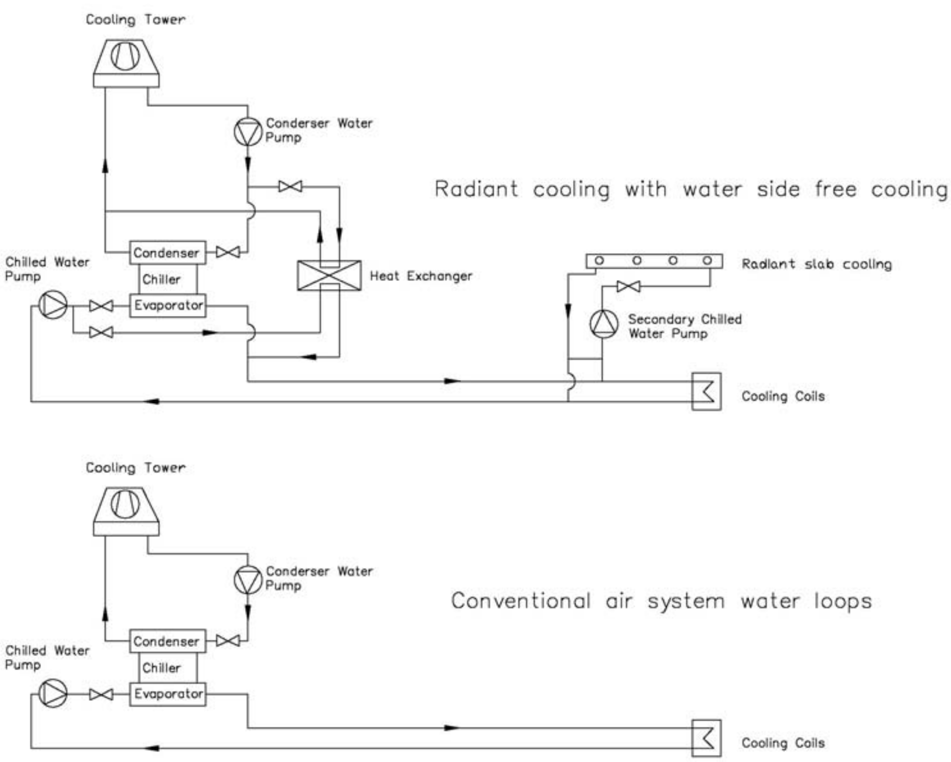

Figure 4 Radiant cooling with DOAS system and VAV system configurations (water side)

Table 2 Simulated HVAC energy uses in mixed and warm climates (continuous operation)

Climate Zone		Zone 4A	Zone 4B	Zone 4C	Zone 3A	Zone 3B	Zone 3C
Generic Description		Mixed-Humid	Mixed-Dry	Mixed-Marine	Warm-Humid	Warm-Dry	Warm-Marine
City		New York, NY	Albuquerque, NM	Seattle, WA	Atlanta, GA	El Paso, TX	Los Angeles, CA
VAV Energy Use (GJ)	Cooling	83	84	29	141	137	80
	Heating	96	70	82	73	63	57
	Fan	119	203	104	139	195	142
	Pump	16	14	11	18	17	15
	Total	314	371	227	371	412	294
RC+CV Energy Use (GJ)	Cooling	76	0	0	113	70	70
	Heating	61	30	48	47	35	13
	Fan	77	77	69	87	78	90
	Pump	62	53	32	75	83	84
	Total	276	160	149	322	266	257
	Savings	12%	57%	34%	13%	35%	13%

Table 3 Comparison of simulated HVAC energy uses in hot climates (continuous operation)

Climate Zone		Zone 2A	Zone 2B	Zone 1A	Zone 2B
Generic Description		Hot-Humid	Hot-Dry	Very Hot-Humid	Very Hot-Dry
City		Houston, TX	Phoenix, AZ	Miami, FL	Riyadh, SAU
VAV Energy Use (GJ)	Cooling	232	183	305	208
	Heating	0	0	0	0
	Fan	149	205	170	231
	Pump	21	19	24	19
	Total	402	408	499	459
RC+CV Energy Use (GJ)	Cooling	166	116	214	108
	Heating	0	0	0	0
	Fan	99	87	111	92
	Pump	73	93	90	104
	Total	339	296	415	304
	Savings	16%	27%	17%	34%

Table 4 Comparison of HVAC energy use in four climate zones with night-time shutdown of air supply

Climate Zone		Zone 6A	Zone 6B	Zone 2A	Zone 2B
Generic Description		Cold-Humid	Cold-Dry	Hot-Humid	Hot-Dry
City		Toronto, ON	Helena, MT	Houston, TX	Phoenix, AZ
VAV Energy Use (GJ)	Cooling	51	42	231	178
	Heating	99	77	10	6
	Fan	127	136	156	203
	Pump	9	10	15	14
	Total	288	265	412	402
RC+CV Energy Use (GJ)	Cooling	47	0	164	111
	Heating	89	70	0	0
	Fan	50	51	85	65
	Pump	54	37	69	79
	Total	240	158	318	255
	Savings	17%	40%	23%	37%