The 2005 World Sustainable Building Conference,
Tokyo, 27-29 September 2005 (SB05Tokyo)

DESIGN OF ENERGY EFFICIENT BUILDINGS WITH RADIANT COOLING SYSTEMS

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Keywords: energy efficiency, radiant slab cooling, building simulation, measurement, holistic design

Summary

Radiant cooling allows improved energy efficiency and thermal comfort. Due to dual functioning as building element and cooling system, the performance of radiant slab cooling is significantly affected by other building components. The dynamic interaction of radiant slab cooling system and other building elements and systems has received relatively little attention. The 2001 completion of the 17,500 m^2 ICT Building at the University of Calgary offered the opportunity to evaluate the post-occupancy operating performance of radiant slab cooling. Based on the ICT operation, this paper explores more effective use of radiant slab cooling technology.

Through simulation with *EnergyPlus* and field measurement, it has found that the energy performance of the ICT Building is not as good as expected, the main problem is the simultaneous heating from air system and cooling from radiant slab system. The control strategy should avoid simultaneous heating and cooling by the air and radiant cooling systems. Combined with radiant cooling, a constant volume, all outdoor air system can be utilized to further advance energy performance. A building envelope that reduces exterior heat gain and the effective exploitation of low quality cooling sources with the thermal storage capability of concrete slabs are important factors to advance building energy performance with radiant slab cooling.

1. Introduction

Providing acceptable and predictable comfort in buildings to protect people from unfavorable environments has long been a human preoccupation. Buildings not only roughly contribute one third of the total energy use and green house gas emissions that cause to global warming (Edwards 1999), some surveys also show that in today’s artificial built environment, around 50 percent of building occupants were not very satisfied with their comfort conditions (Watson et al., 2001).

In commercial buildings, the prevalent environmental control systems are mixed air systems, with cooled air used to condition building space. Due to the opportunity to reduce energy use and the dissatisfaction with mixed air cooling systems, radiant cooling technology has received increasing attention in recent years, especially in Europe. Although some theoretical studies of radiant slab cooling have been conducted, the actual energy performance of operating buildings has seldom been reported. The effectiveness of radiant slab cooling systems and post-occupancy indoor conditions are seldom investigated (De Carli et al., 2002).

The 2001 completion of the 17,500 m^2 seven-story Information and Communications (ICT) Building at the University of Calgary, the first multi-floor building with radiant slab cooling in North America (McDonell, 2003), allowed a holistic survey of energy and thermal performance of an operating radiant slab cooling system.

2. Discription of the ICT Building

The ICT Building consists of two main parts: the two-storey base floor (levels 1-2) includes a food and study court and lecture theatres. The tower has six floors (levels 2-7) of laboratories, classrooms, faculty offices, and graduate student workstations. North and south service zones contain stairs, washrooms, and student lounges (Figure 1).

Figure 1 Southwest perspective view of ICT Building

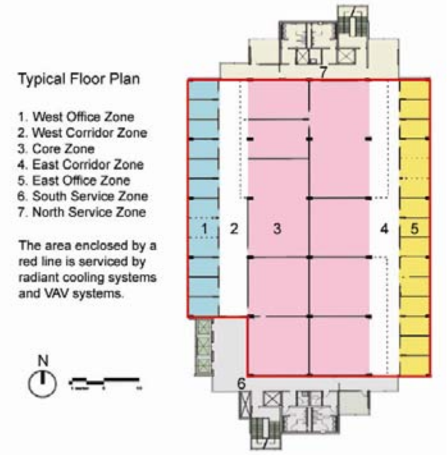

Figure 2 A typicl floor plan

The building is oriented north-south with most faculty offices located at the west and east perimeter (Figure 2). Much of the cladding is a curtain wall (spandrel effective U-coefficient of about 1.0 W/m^2 ^{o}C) with low-E glazing (U-coefficien tof about 2.2 W/m^2 ^{o}C and window-to-wall area ratio around 0.55 for the faculty offices).

Three conventional variable air volume (VAV) systems with terminal reheat serve the main floor. Another VAV system with reheat provides ventilation and heating/cooling to the tower. The radiant slab provides cooling for the tower except the service zones (Figure 2). In addition, radiant heating panels provide heating in all perimeter spaces of the building. The chilled water and hot water are provided by a campus system, with thermal meters to monitor the use at each building.

The radiant slab cooling system circulates 16^{o}C to 21^{o}C constant flow water in polyethylene pipes (embedded 50mm above the underside of the 200mm thick concrete slabs). As there is no insulation layer in the slabs of the ICT Building, radiant cooling acts upward and downward almost equally, while the convective heat exchange is mainly through the ceiling surface with higher temperature differences between air and ceiling surfaces than between air and floor. This chilled water is a mixture of water 1) discharged from air-handler cooling coils, 2) provided by the chilled water network (via heat exhanger) and 3) recirculated water from the radiant cooling system. On a typical floor, the radiant slab is separated into three general zones: east, west and core, responding to load variations.

3. Field Measurement

In order to investigate the thermal performance of the ICT Buiding with radiant slab cooling, indoor thermal conditions were measured in August 2004. An east private office and a core computer laboratory were chosen as the measurement locations. Monitored thermal variables include air temperature (MAT), air velocity, relative humidity and operative temperature (OPT). In this paper, only the measured operative temperature and mean air mperature are presented. Operative temperature is the average of air temperature and mean radiant temperature (MRT) when the air velocity is below 0.2 m/s (ASHRAE, 2004).

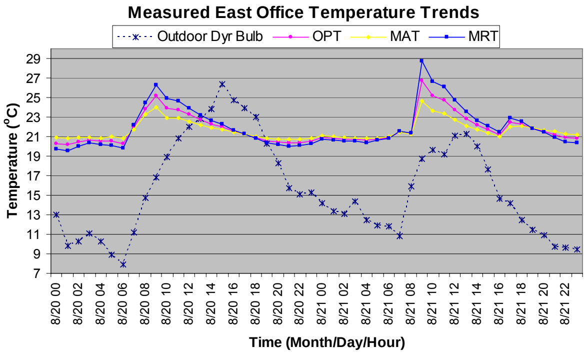

Figure 3 Perimeter office temperature trends

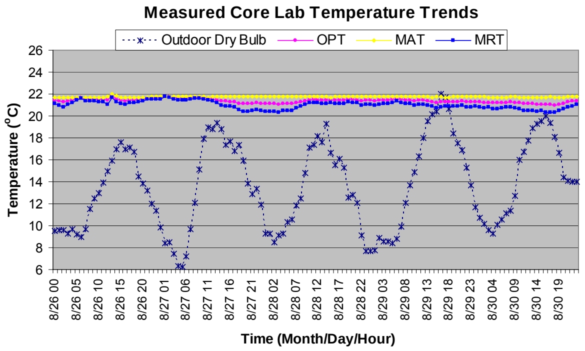

Figure 4 Core lab temperature trends

The monitored temperature trends in the private office is shown in Figure 3; it can be seen that the operative temperature in this private office may reach as high as 27 °C even when the outdoor temperature was only about 18.7 °C. This indicates that the solar radiation has an important impact on the space operative temperature wjhen the office receives morning sunlight. It also can be seen that the space air temperature was above 21 °C all day.

Figure 4 shows the temperature trends in the computer laboratory, where cooling is needed thoughout the year. As can be seen, compared to the perimeter office, the core area space has relatively stable temperatures: the room air temperature was maintained about 22 °C and room operative temperature varied around 21.5 °C. The temperature profiles indicated that there was no control stategy for nighttime or holiday temperature set back.

4. Buildin Simulation

4.1 Whole building simulation

Building energy simulation programs give building designers the capability for non-trivial energy performance analysis and assessment. Until recently, there was a lack of public domain tool to analyze the energy performance of radiant slab cooling systems. With the release of *EnergyPlus*, which incorporates the best features of *BLAST* and *DOE-2*, Strand et al. (2002) developed a transfer function radiant heating and cooling model.

In this study, *EnergyPlus* was chosen to simulate the ICT energy performance. The main construction materials in the simulation are listed in Table 1. It should be noted that important characteristics, such as the thermal conductivity of concrete may vary from 0.3 to 2.0 W/m K in a real situation.

Due to limitations in modelling VAV systems with large air flows within *EnergyPlus*, two models were used – one for the base and one for a typical tower floor; results were then aggregated. Simulated uses agreed well with measured heating and cooling values (Figure 5, Figure 6). Also, simulated temperature trends are similar to the field measured results.

Relative to the metered annual cooling energy use of 4,037 GJ for the year 2004, simulated annual cooling energy is 4,217 GJ, about 4.5% higher. In comparison to the measured 6,771 GJ of annual heating energy, the simulated value is 6,955 GJ, only 2.7% higher. In January and February 2004, the radiant cooling systems in the ICT Building only ran half a month in each month, and in December 2004 the radiant cooling systems only ran one day. The simulation model predicts monthly cooling energy uses very well based on actual operating schedules (Figure 5).

Table 1: Building Constructions and Thermal Properties of Materials Used in Simulation

Type of Construction	Description of Layers (from outside to inside)	Thickness (m)	Thermal Conductivity (W/m.K)	Density (kg/m^3)	Specific Heat (J/kg.K)	Thermal Resistance (m^2.K/W)
Curtain Wall	Plate-Glass Cladding	0.006	0.76	2710	837	
	Roxul-Polystyrene	0.13	0.039	56	710	
	Aluminum Panel	0.001	221.4	2739.15	890	
Wall-Mass	Clay Tile-Hollow	0.101	0.52	1120	880	
	Polystyrene Foam	0.075	0.029	28.8	1210	
	ConcBlock	0.2	1.67	1840	840	
Wall-Aluminum	Aluminum Siding	0.0095	221.4	2739	890	
	Polystyrene Foam	0.075	0.029	28.8	1210	
	ConcBlock	0.2	1.67	1840	840	
Lower-Roof	Roof Gravel	0.05	1.667	1600	790	
	Polystyrene Foam	0.075	0.029	28.8	1210	
	Menbrane-Plasticfilm	0.00025	0.011	1120	1460	
	Polystyrene Foam	0.1	0.029	28.8	1210	
	Gypsum Sheathing	0.013	0.161	800	1090	
Interior Partition	Plasterboard	0.01	0.16	950	840	
	Air Space					0.1604
	Plasterboard	0.01	0.16	950	840	
Concrete Slab	Carpet	0.005	0.06	160	2500	
	Concrete Floor 150	0.15	1.6	2000	830	
	Concrete Floor 50	0.05	1.6	2000	830	

4.2 Simulation Comparison

In order to further study the energy performance of the ICT radiant slab cooling system, a typical floor without the north and south service zone (Figure 2) was modeled using a conventional VAV-reheat system to compare the energy use with the combined radiant slab and VAV system (RC+VAV). The air flow rate and the fan size were increased accordingly to meet the cooling load in the conventional VAV system. The simulation results are listed in Table 2 below. It should be noted that control set points in both systems were based on indoor air temperature and there was no exhaustive effort made to exactly match the indoor temperatures between these two systems for a year time period.

The annual cooling energy use in the RC+VAV system is about 380% that in the conventional VAV system. The annual heating energy use in the RC+VAV system is 160% that in the conventional VAV system (in the simulation models, the minimum outdoor air flow rate in the conventional VAV system and RC+VAV system are set as the same). As can be seen in Table 2, supply fan energy use can be halved by using radiant cooling, although pump energy use increases. The RC+VAV system would accrue additional fan energy savings if return and exhaust fans were taken into account.

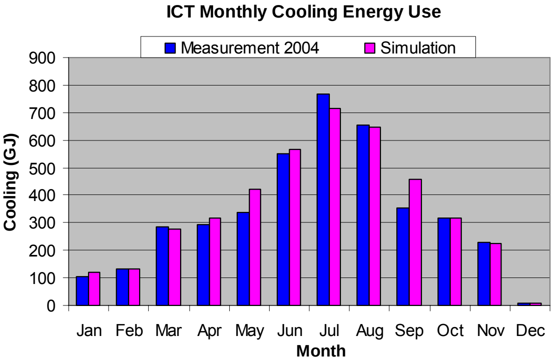

Figure 5 ICT Monthly cooling energy use

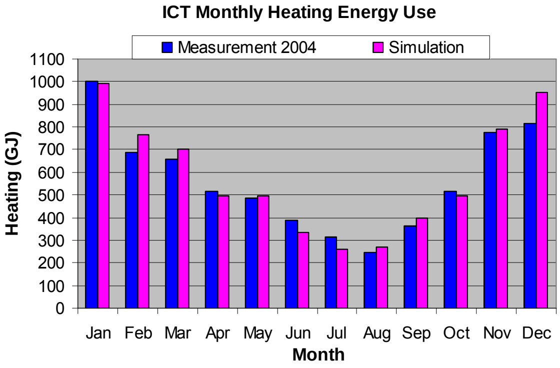

Figure 6 ICT Monthly heating energy use

The monthly cooling energy use profile (Figure 7) shows that the cooling energy use in the RC+VAV system is always higher than that in the conventional VAV system, and the difference increases in winter. The monthly heating energy use profile (Figure 8) shows that the heating energy use in the RC+VAV system is also always higher than that in the conventional VAV system, and the difference increases in summer.

Table 2 Annual Energy Uses for a Typical Floor (not including return and exhaust fans)

System	Cooling (GJ)	Heating (GJ)	Fans (GJ)	Pumps (GJ)	Lighting & Equipment (GJ)
VAV	176	358	228	2	412
RC+VAV	662	583	122	14	412

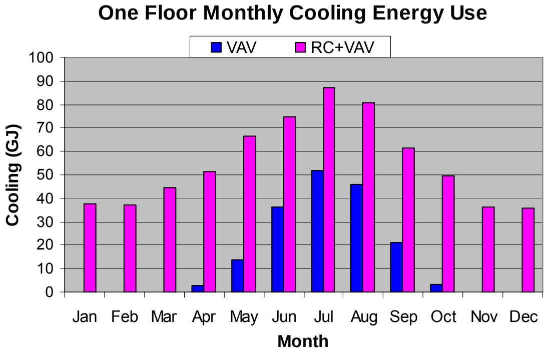

Figure 7 One floor monthly cooling

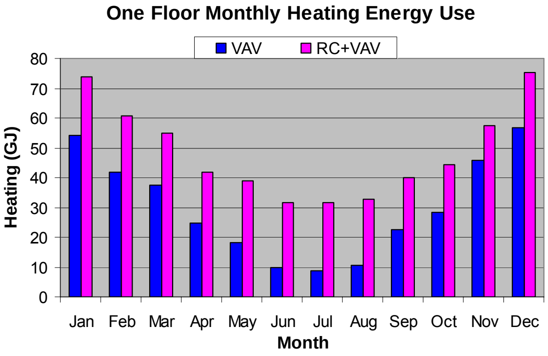

Figure 8 One floor monthly heating

5. Discussions

5.1 Improving existing system control strategy

From metered energy end uses and the above simulation comparison, it can be found that the current energy performance of ICT Building is not as good as would be expected. The following factors are considered to contribute to the higher cooling and heating energy uses:

- In the conventional VAV system, almost free cooling can be utilized all winter, but for the RC+VAV system in the ICT Building, most of the sensible cooling load is taken by the radiant cooling system. For perimeter zones, supplying chilled water to slabs during winter causes both high cooling and heating energy use, because the perimeter zones typically need to be heated instead of cooled. As shown in Figure 3, when the radiant cooling system was essentially unused during a winter month (it only ran one day in December 2004), the cooling energy use decreased dramatically.

- In the simulation, with radiant cooling, generally the mean radiant temperature in the RC+VAV system would be 1°C lower than that in the conventional VAV system when two systems are controlled to the same air temperature. When buildings are controlled by air temperature thermostats, the cooling setpoint can be increased 1-2 °C with equivalent thermal comfort conditions for radiant systems. For the core area spaces, when the air temperature was maintained between 22-23 °C in the summer, the indoor operative temperature will be on the cool side of comfort range according to ASHRAE Standard 55 (2004).
- Due to the thermal mass of the concrete slab, "coolness" stored in the slab may result in low indoor temperature at night. The simulation results show that the air temperature in perimeter offices would drop to around 18-19 °C at summer night without reheat. Since the perimeter (faculty) offices were observed to be essentially vacant at night, it is unnecessary to heat perimeter offices to 21 - 22 °C at night, which may cause simultaneous air system heating and radiant slab cooling. For the real building, it was found that reheat coils were activated at night in the core areas to prevent overcooling throughout the year. Without reheat, the indoor air temperature at night in the core areas would drop to around 20-21 °C. The reheat process could contribute to the higher heating energy use in the RC+VAV system, especially in summer, when the slab supply water temperature is lower.

Based on the above analysis, the following system control strategy (Retrofit 1) is proposed to coordinate the operation of the radiant cooling and air systems without modifying the existing building systems:

- Only run the radiant slab cooling system from May 1 to September 30; at other times employ free cooling via the air distribution system;
- Increase the slab water temperature to 21°C for the core zone during May-September; increase cooling setpoint (air temperature) to 24 °C and shut off the reheat coils for the core zone to avoid conflicts between radiant and air systems;
- Reset perimeter zone slab water temperature (constant flow) from 21 °C to 16 °C for outdoor dry bulb temperatures 10 °C to 24 °C to reduce overcooling of perimeter zones; increase cooling setpoint to 23 °C; set back heating setpoint of perimeter zones to 18°C at night; and
- Use free cooling more extensively through air systems during May-September.

The simulated result is presented in Table 3 below. Both heating and cooling energy uses can be greatedly redced with some increasement of fan energy use.

Table 3 Simulated energy uses with Retrofit design 1(change system operation)

System	Cooling (GJ)	Heating (GJ)	Fans (GJ)	Pumps (GJ)
Retrofit 1	174	268	135	2.3

5.2 Improving existing systems

To further advance the building energy performance, other opportunities exist:

- In Calgary's cold, dry climate, the outdoor wet bulb temperature only exceeds 16 °C about 20 hours per year. This would allow "low quality" energy sources to be used for cooling since the required minimum chilled water temperature is only 16 °C in the ICT Building. The water temperature from evaporative based condensers is close to outdoor wet bulb temperature (Strand, 2003);

- The perimeter zones facing west and east have high cooling loads due to summer solar heat gains, which produces indoor mean radiant temperature as high as 29 °C. This indicates the need for control of solar radiation. Otherwise, the VAV system must offset these cooling load variations;
- The core zone has a lower cooling load fluctuation and peak cooling load per unit floor area than the perimeter zones. With radiant slab cooling, 100% outside air system may be used with the airflow rate according to the ventilation requirement to further reduce fan energy use. Either conventional constant volume make-up air systems or displacement ventilation systems with heat recovery can be considered.

Based on the above, the following strategies can be exploited:

- Add exterior overhangs (depth 1m, tilted 45°) to reduce solar heat gain for perimeter offices during summer;
- Link the radiant cooling system to a condenser loop (cooling tower etc.) instead of the chilled water network to utilize water side economizer (free cooling). For the core areas, even the domestic water can be utilized for cooling; and
- Set up a separate constant air volume (CAV) system with 100% outdoor air and heat recovery unit for the core areas to meet the requirement for outdoor air and latent cooling load; the air flow rate meets the ventilation requirement for air quality according to ASHRAE 62 (ASHRAE 2001);

As can be seen in Table 4, the cooling and heating energy uses are only 26% and 65%, respectively, to that in Retrofit design 1; the fan energy use also can be reduced 24%.

Table 4 Simulated energy uses with Retrofit design 2 (change systems)

System	Cooling (GJ)	Heating (GJ)	Fans (GJ)	Pumps (GJ)
Retrofit 2	46	175	102	12

6. Conclusions

Acting in the dual role of building element and cooling system, a radiant slab cooling system and its performance are sensitive to complex thermal processes and affected by other building components. Although the combined radiant cooling and air system provides the possibilty to improve building energy performance, from the above discussion, it was found that the current energy performance of the ICT Building is not as good as expected for radiant cooling. Special attention must be paid to ensure a successful design with radiant slab cooling system:

- Combined with radiant slab cooling system, an outdoor-air only ventilation system with heat recovery can significantly reduce energy use;
- With a radiant system, it is preferable to control indoor operative temperature since radiant cooling systems can provide the same operative temperature at higher air temperature, compared to conventional mixed air systems;
- The thermal characteristics of the building envelope play a significant role in the performance of radiant cooling systems. Solar radiation via glazing is very significant. If the exterior heat gain via the building

envelope is too high, the slab supply water temperature may have to decrease accordingly, then the low water temperature may cause condensation or low night temperatures due to the thermal mass of concrete slabs;

- Coordination between radiant and air systems is necessary to ensure the effective environmental control. Due to the separate functions, simultaneous cooling by the radiant slab system and heating by the air system may occur. Selecting the appropriate slab water temperature is important to reduce simultaneous heating and cooling, and at the same time, to provide acceptable thermal comfort conditions during occupied hours;
- Combining passive cooling with the thermal storage capability of concrete slabs can reduce the cooling energy requirement. The chilled water temperature in a conventional air system is about 6 ^{o}C, while the slab water temperature can be 16 ^{o}C or higher. This high water temperature greatly increases the possibility of using a broad range of low quality cooling sources, like cooling towers, ground water or even domestic water.

The building energy performance relies not only on the individual efficiency of each building element and system, but also on the overall effectiveness of the whole building as an integrated system. The optimal solution for utilizing radiant cooling will be a holistic design approach: first, a well designed building envelope can keep the thermal transfers to a low level and within the cooling capacity of radiant sytem, then the independent air system only needs to provide ventilation, and the possibility of utilizing low quality cooling sources can be maximized.

Acknowledgements

The authors acknowledge the financial support from Alberta Innovation & Science, Natural Resources Canada, and the Natural Sciences and Engineering Research Council of Canada. Murray Sloane and Tom Humphries of Campus Infrastructure (CI) provided information. Craig Smith of CI and Bev Shevchenko of Computer Science provided access for measurements. Dr. Michael Witte of Gard Analytics provided extensive support with respect to *EnergyPlus*.

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