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AN INTEGRATED STUDY OF RADIANT SLAB COOLING SYSTEMS THROUGH EXPERIMENT AND BUILDING SIMULATION

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ABSTRACT

Radiant cooling systems for thermal comfort in commercial buildings are new to North America. The University of Calgary's ICT Building has a hybrid radiant slab-mixed air system that offers an opportunity to evaluate operating performance. Through integrated field measurements and building simulation with *EnergyPlus*, it was found that the building energy performance could be improved by reducing conflicts between systems, especially simultaneous heating and cooling. Control strategies to coordinate air and radiant system operation are crucial to improve the overall building energy performance. Use of "low quality" cooling sources with radiant slab cooling was also considered.

INTRODUCTION

Most energy use in buildings is to maintain desired thermal and visual comfort conditions through heating, air conditioning, ventilation and lighting. Traditional air-based HVAC systems condition spaces via cooling/heating large volumes of air. In recent years, hydronic radiant cooling, which is defined as 50 % or more of energy transfer accomplished through radiation (ASHRAE, 2000), has been increasingly applied in western European countries, especially Germany and Switzerland (e.g., De Carli and Oleson, 2002).

A radiant system combined with a ventilation system has the potential to provide better thermal comfort conditions and energy performance than conventional mixed air systems. According to a report to the U.S. Department of Energy of (DOE), radiant cooling is one of the most effective methods for space cooling in terms of comfort and efficiency (Roth et al., 2002). Although some theoretical studies of radiant slab cooling (e.g. Olesen, 1997; Strand and Pedersen, 2002), and some field measurement (e.g. De Carli and Olesen, 2002) have been conducted, the combined energy performance and thermal conditions of existing buildings have seldom been reported. The completion of the seven-storey 17,500 m^2 Information and Communications (ICT) Building at the University of Calgary in 2001, the first multi-floor facility with radiant slab cooling system in North America (McDonell, 2003), provided an opportunity to investigate the combined energy performance and thermal conditions.

SIMULATION AND MEASUREMENT

Calgary climate and the ICT Building

Calgary is located in western Canada (Latitude 51.1, Longitude -114) at 1084 m above sea level. Calgary's mean annual temperature is about 4 ^{o}C. The ambient temperature exceeds 18 ^{o}C only about 800 hours per year and 25 ^{o}C only about 60 hours per year.

The ICT Building has two main parts: the two storey base (floors 1-2) is stretched along a ramp connecting two adjacent buildings. It includes a food and study court and lecture theatres. The tower (floors 2-7) of laboratories, classrooms, faculty offices, and graduate student workstations. North and south service zones contain stairs, washrooms, and student lounges (Figure 1). 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 with low-E glazing (window-to-wall area ratio around 0.55 for the faculty offices).

Figure 1 Perspective view of ICT Building from southwest

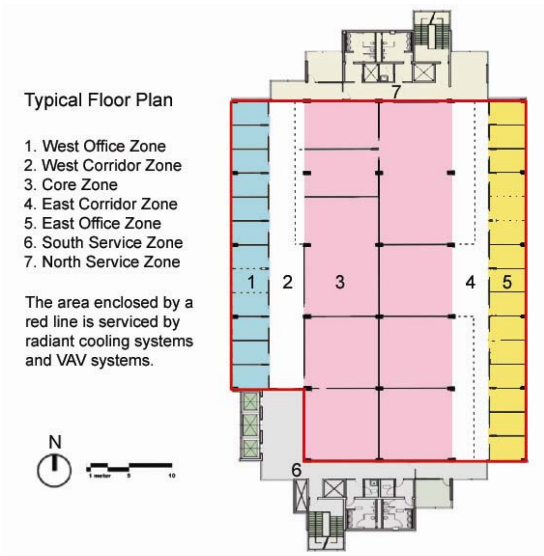

Figure 2 A typical floor plan of ICT Building

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 floors 2-7. The radiant slab provides cooling in 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 constant flow, high-temperature water (around 16 ^{o}C to 21 ^{o}C) in polyethylene pipes embedded in the concrete slabs. 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 primary zones: east, west and core, responding to load variations. The slab cooling system was intended to handle the base sensible cooling load from internal heat gain due to anticipated large equipment gains. The VAV system was intended to offset short-term cooling requirements, particularly solar gains and classroom occupant loads.

Unlike most chilled ceiling systems, there is no insulation layer in the slabs of the ICT Building. Pipes are embedded 50mm above the underside of the 200 mm thick concrete slabs. With both cooled ceiling and floor, 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.

The ICT design has some significant weaknesses. Radiant systems are less effective in offsetting large heat gains and losses at specific points. The high window-to-wall ratios at the ICT building, without shading, lead to large peak solar gains. The curtian wall has an effective U-coefficient of about 1.0 W/m^2 ^{o}C, leading to large perimeter heat losses in Calgary's cold climate.

Whole building simulation

First, a simulation model using VAV systems was built in *EE4/DOE-2* (*DOE-2* is the simulation engine of *EE4*) and the simulation results were compared to metered chilled and hot water use. The simulated 2002 cooling energy was 58% lower than the metered use; simulated heating energy use was 20 % lower than monitored (Love, 2003). Feng (2004) found very good agreement of simulated and measured energy use for weekly heating in a 550 m^2 building heated by a radiant slab on grade, based on an *EE4/DOE-2* model. Other research (Zweifel and Koschenz, 1993) showed that it is possible to approximate radiant system performance with *DOE-2* by special modelling techniques. However, modeling a radiant system in detail, especially short-term (hourly) behaviour, is beyond the basic design of *DOE-2*.

Within the new simulation program *EnergyPlus*, Strand and Pedersen (2002) developed a radiant heating and cooling model by using the conduction transfer function method. Chantrasrisalai et al's (2003) study of modelling radiant cooling (without ventilation) in *EnergyPlus* showed that system performance is significantly affected by the interplay of complex thermal processes. Results are very sensitive to values of thermal and control parameters.

In this study, version 1.2.1 of *EnergyPlus* was chosen to simulate the ICT energy performance, and to evaluate control strategies. 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. Simulation results agreed well with measured heating and cooling values (Figure 3, Figure 4). It should be noted that the simulation results are based on the Calgary weather year for energy calculations. Further, the most recent measured energy data were used because the building is more fully occupied than in 2002, and systems have been adjusted by the operating staff since then.

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 use very well, based on actual operating schedules (Figure 3).

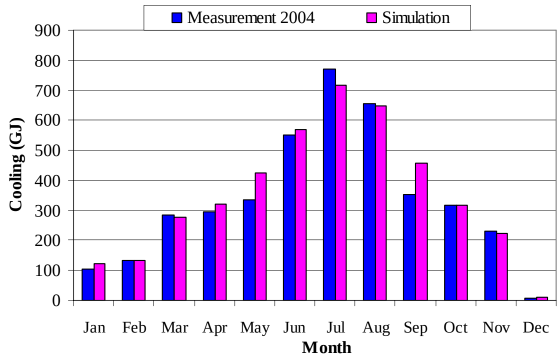

Figure 3 Measured and simulated monthly cooling energy uses for ICT Building, 2004

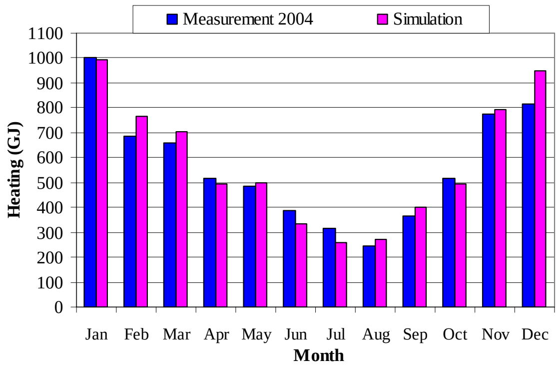

Figure 4 Measured and simulated monthly heating energy uses for ICT Building, 2004

Field measurement

Indoor thermal conditions were measured, including air temperature (MAT), air velocity, relative humidity and operative temperature (OPT). In this paper, only the measured operative temperature and mean air temperature 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).

An east private office and a core computer laboratory were chosen as the measurement locations. The field measurements were used to fine tune the simulation model and to evaluate the building control system rather than to validate the simulation program. The simulated temperature trends in the core zone and the east zone during the daily cycle (Figures 6, 8) were similar to the measured values in the corresponding two spaces (Figures 5, 7), considering the differences between actual conditions and simulation model input parameters. For example, the simulated temperature is the mixed temperature of the whole east zone, while the measured data is the temperature in one office. The slab supply water temperature in simulation may be different from actual slab supply water temperature.

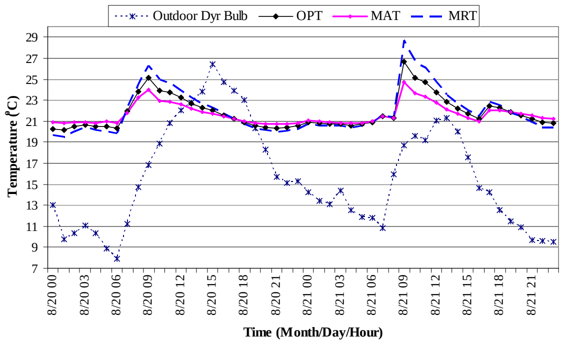

Figure 5 Measured temperature trends in an east side unit office

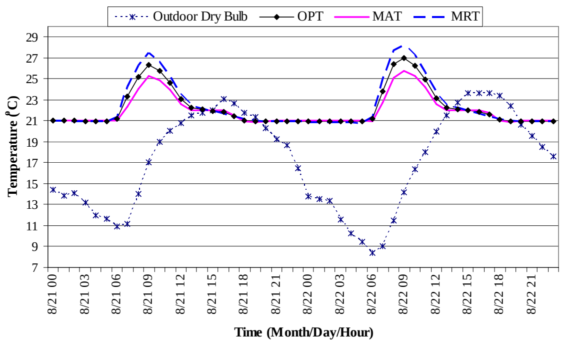

Figure 6 Simulated temperature trends in the east zone with typical weather data

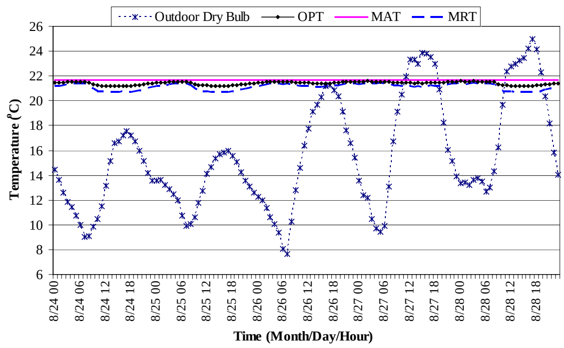

Figure 7 Measured temperature trends in a core computer lab

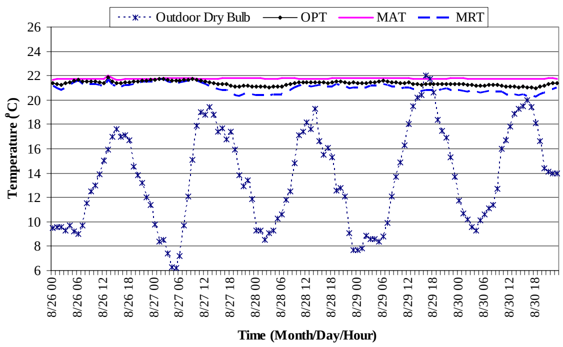

Figure 8 Simulated temperature trends in the core zone with typical weather data

Simulation comparison: energy performance of hybrid radiant slab-VAV and conventional VAV

In order to further study the energy performance of the ICT slab cooling system, a typical floor (except the north and south service zones, see Figure 2) was modeled with a conventional VAV system to compare the energy use with the hybrid radiant slab-VAV system (RC+VAV). The conventional VAV-reheat system would increase air flow to meet the cooling load; fan size was adjusted proportionally to the maximum air flow requirement. The simulation results are listed in Table 1 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 the one year simulation period.

The annual cooling energy use in the RC+VAV system is about 380% that in the conventional VAV system. This may explain why the ICT cooling energy use projected by the *EE4-DOE2* VAV model was much lower than the 2002 measured value. 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 1, 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.

A monthly cooling energy use profile (Figure 9) 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. This is because the conventional VAV system can utilize almost all free cooling in winter, but for the RC+VAV system in the ICT Building, most of the sensible cooling load is taken by the radiant cooling system. 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. For perimeter zones, supplying chilled water to slabs during winter causes both high cooling and heating energy use (Figure 10), because the perimeter zones typically need to be heated instead of cooled.

Table 1
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

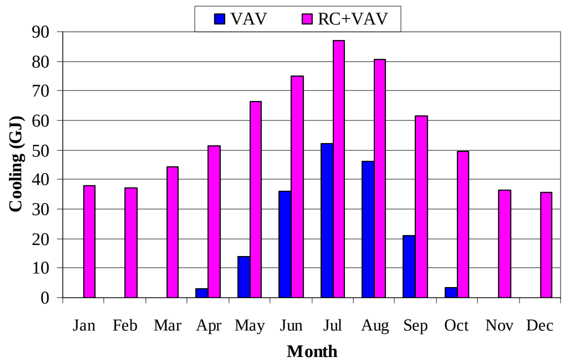

Figure 9 Month cooling energy uses in conventional VAV system and RC+VAV system

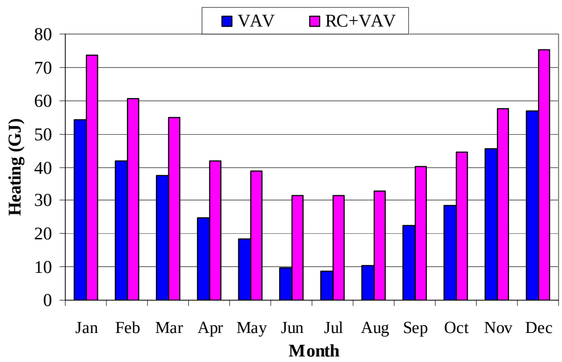

Figure 10 Monthly heating energy uses in conventional VAV system and RC+VAV system

Although the same cooling setpoint (air temperature) was used in the simulation models because operative temperature cannot be used in *EnergyPlus* when a radiant system is combined with a mixed air system, generally the operative temperature in the RC+VAV system would be 0.5-1 ^{o}C lower than that in the conventional VAV system.

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 ^{o}C on summer nights unless reheat was used. 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 ^{o}C. The reheat process could contribute the higher heating energy use in the RC+VAV system (Figure 10). Selecting the appropriate slab supply water temperature and operation schedule are important to reduce simultaneous heating and cooling.

Retrofit design

Based on the above analysis, the following system control strategy (Retrofit 1) was 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 supply water temperature to 21 ^{o}C for the core zone during May-September 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 ^{o}C to 16 ^{o}C for outdoor dry bulb temperatures 10 ^{o}C to 24 ^{o}C to reduce overcooling of perimeter zones; and
- Use free cooling through air systems more extensively during May-September.

The energy end uses for the RC+VAV with Retrofit 1 are listed in Table 2. It can be seen that both the annual heating and cooling energy uses are reduced. However, compared to that of the conventional VAV system, the annual cooling energy use of the

RC+VAV system is still about 16 % higher. Inspection of simulation results indicates that the higher operative temperature and more extensive use of free cooling in May and September are the the main factors contributing to lower cooling enery use for the conventional VAV system.

Table 2
Simulated energy uses with Retrofit design 1

SYSTEM	Cooling (GJ)	Heating (GJ)	Fans (GJ)	Pumps (GJ)
Retrofit 1	203	318	161	3

With radiant slab cooling, the possible energy and peak power savings may include the following: 1) reduced fan energy use (Feustel and Stetiu, 1995); 2) the possibility of providing the same thermal comfort conditions with higher air temperatures (Watson and Chapman, 2002); and 3) increased refrigeration efficiency of chillers by allowing higher evaporation temperature (CIBSE, 1998). It also allows use of a broad range of alternative cooling, including heat pumps, geothermal exchange, cooling towers, and other renewable cooling sources (Olesen et al. 2002).

Based on the existing operation of the ICT Building, the following energy conservation opportunities exist:

- For perimeter offices, it is unnecessary to heat to 21-22 ^{o}C at night in summer since the perimeter (faculty) offices were observed to be essentially vacant at night. Doing so causes simultaneous air system heating and radiant slab cooling;
- In a radiant system, it is preferable to control operative temperature, but in the ICT Building the room temperature control is based on air temperature thermostats; and
- In Calgary's cold, dry climate, the outdoor wet bulb temperature only exceeds 16 ^{o}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 ^{o}C in the ICT Building. The water temperature from evaporative based condensers is close to outdoor wet bulb temperature (Strand, 2003). Local rivers are glacier fed and water temperatures are typically about 10 ^{o}C.

Based on the above, the following strategies (Retrofit 2) can be developed from Retrofit 1:

- Set back heating setpoint of perimeter zones to 18 ^{o}C at night;
- Increase cooling setpoint (air temperature) for perimeter zones from 22 ^{o}C to 23 ^{o}C and increase cooling setpoint from 22 ^{o}C to 24 ^{o}C for core zones when the radiant system is running;
- 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 zone, the radiant system can utilize the domestic water for cooling as the required supply water temperature is only 21 ^{o}C; and
- Set the radiant slab as the primary cooling system in summer to fully utilize water side economizer (low quality cooling source).

The simulated energy uses are presented in Table 3 below; both cooling and heating energy use can be greatly reduced with some increased fan energy use (including the fan energy use in cooling towers).

Table 3
Simulated energy uses with Retrofit design 2

SYSTEM	Cooling (GJ)	Heating (GJ)	Fans (GJ)	Pumps (GJ)
Retrofit 2	77	189	145	6

Figure 11 shows the operative temperature trends with retrofit design 2 in three zones (west office, core, east office) during extremely hot (Jul. 20-Jul. 26) and typical (Aug. 24-Aug 30) hot weeks, based on typical Calgary weather data. Figure 12 shows the operative temperature trends during extremely (Dec. 15-Dec. 21) and typical (Dec. 22-Dec. 28) cold weeks.

During the extremely hot week, the operative temperatives in perimeter offices exceed 27 ^{o}C only 2-3 hours on the hottest days. In the typical hot week, operative temperatures in perimeter offices are

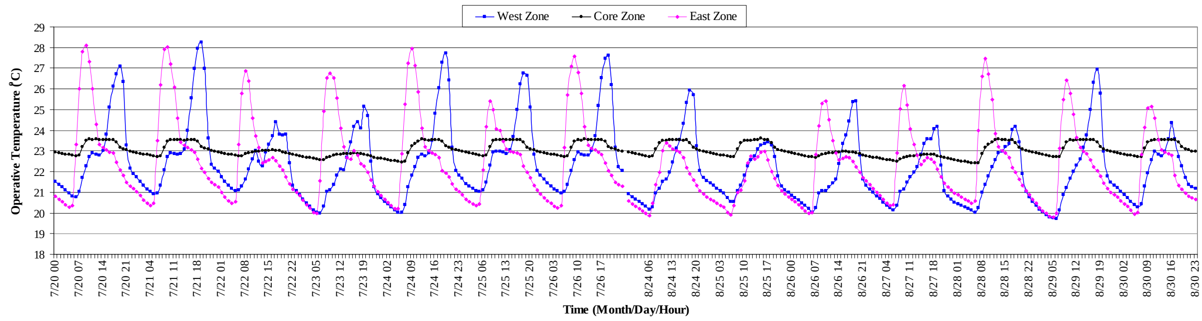

Figure 11 Simulated operative temperature trends in extremely hot week (July 20-July 26) and typical hot week (Aug. 24-Aug. 30)

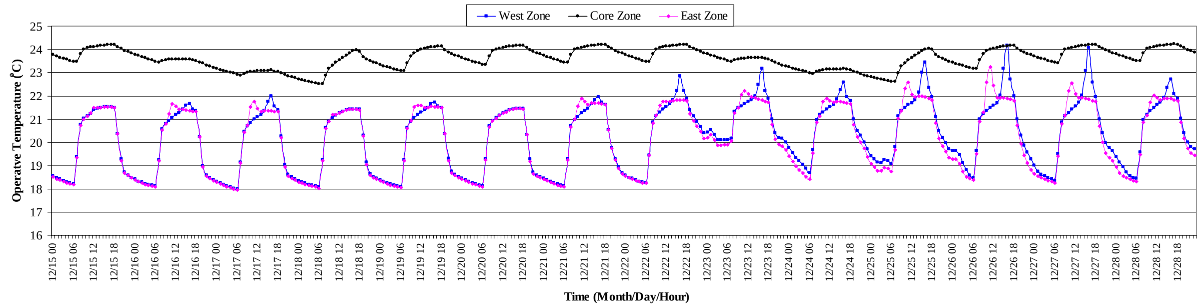

Figure 12 Simulated operative temperature trends in extremely cold week (Dec. 15-Dec. 21) and typical cold week (Dec. 22-Dec. 28)

almost all below the comfort upper limit of about 27 °C (ASHRAE, 2004). Although during the extremely cold week, the perimeter office operative temperatures are somewhat lower than those during the typical cold week, the operative temperatures during occupied times (08:00-18:00) are always above the lower limit of 21 °C (ASHRAE, 2004). In the core zone, the operative temperature is around 22.5-24.2 °C all year, well within the comfort range.

Further Consideration

To further advence the ICT energy performance, other alternatives may be considered. 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 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 limited to the ventilation requirement (normally around 20 % of total air flow in mixed air systems) to further reduce fan energy use. Either conventional constant volume make-up air systems or displacement ventilation systems with heat recovery can be considered. These will be evaluated in future studies.

CONCLUSIONS

This study has investigated the energy performance and thermal conditions of the ICT Building with radiant slab cooling. As the radiant slab acts in the dual role of building element and cooling system, the building energy performance is sensitive to complex thermal processes and affected by other building components and systems. This makes the modelling process time-consuming. Through simulation and measurement, this study found that the ICT Building energy is not as good as would be expected for radiant cooling technology. Simulation comparison with a conventional VAV system shows that the cooling energy use for the hybrid radiant slab-VAV system is much higher. The analysis of simulation and measurement results revealed that the main cause of high energy use is the control strategy for the combined radiant cooling-air system. Special attention must be paid to avoid simultaneous cooling by the radiant slab cooling system and heating by the air system (especially the slab supply water temperature and operation schedule), and to provide acceptable thermal comfort conditions for occupants.

The main energy benefit of using radiant cooling is reduced fan energy use. Cooling energy use may not be reduced if air temperature control is used as in a conventional air system. Radiant slab cooling also facilitates the usage of “low quality” cooling sources to decrease cooling energy use.

Although the radiant slab cooling system itself has potential drawbacks, such as the possibility of condensation, a good control strategy can allow good performance to be achieved. The keys to a successful radiant slab cooling system are its efficiency and more importantly on its effectiveness (design synergy with other building components and systems).

ACKNOWLEDGEMENT

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