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THERMAL COMFORT AND ENERGY PERFORMANCE OF CHILLED CEILING SYSTEMS

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Abstract: Chilled ceiling systems are a relatively new approach to cooling and they have been applied in Europe and other countries for many years. The technology is based on ceiling-based radiant cooling panels coupled with chilled water pipes or coils. By combing convection and radiation, these systems have the potential to enhance thermal comfort and reduce energy use in air-conditioned buildings. This research studied the basic principles and key characteristics of chilled ceiling systems in order to assess their potential benefits on thermal comfort and energy performance. Field studies in two pilot projects in Hong Kong were carried out to investigate the system performance and practical considerations. Building energy simulation was applied to assess the potential benefits of the system on building energy performance. It is found from the field studies that the thermal comfort can be maintained in most of the time but some occupants feel that the air movement is sometimes too low. As compared with the conventional all-air systems, the chilled ceiling systems can reduce energy requirements by increasing chilled water temperature, decreasing supply air flow, downsizing air handling equipment and promoting higher room temperature. The results of building energy simulation show that the fan energy saving is the most important component and the percentages of energy saving for the HVAC system (19.8%) and the whole building (12.1%) are significant.

Keywords: Chilled ceiling system; thermal comfort; energy performance

冷却吊顶系统的热舒适度和节能性能

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摘要：冷却吊顶系统是一个相对较新的冷却方法，在欧洲和其他国家已应用多年。该技术是基于冷冻水管道或盘管联结的天花板辐射冷却面板。这些系统通过结合对流和辐射，有潜力以提高热舒适度，并减少空调建筑物的能源使用。本研究探讨冷却吊顶系统的基本原理和主要特点，以评估其对热舒适性和节能性能潜在的好处。在香港的两个试点项目，进行了系统性能的调查和实际的考虑。并且应用建筑能耗模拟，来评估系统性能的潜在建筑节能好处。从研究试点项目发现，系统可以在大部分时间保持热舒适性，但也一些用户感到空气的流动有时过低。冷却吊顶系统与传统的全空气系统相比，可降低冷冻水温度增加的能源需求，减少空调供应送风量，削减空气处理设备，并促进更高的室温。建筑节能模拟分析结果表明，风机节能是最重要的组成部分，对空调系统(19.8%)和整个建筑(12.1%)的节能百分比结果是显著的。

关键词：冷却吊顶系统；热舒适度；节能性能

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1. INTRODUCTION

Chilled ceiling systems have been used in Europe since the middle of 1980s (Virta, 2004) and they are now becoming popular in other countries (Antonopoulos *et al*., 1998; Castillo and Tovar, 2012; Chakroun *et al*., 2011; Dieckmann and Brodrick, 2004; Ge *et al*., 2012; Hao, *et al*., 2007; Mumma, 2001; Vangtook and Chirarattananon, 2006). These systems have potential to resolve the weaknesses of existing heating, ventilation and air conditioning (HVAC) systems. It is believed that they can create a more comfortable indoor thermal environment with lower energy consumption (Diaz and Cuevas, 2011; Imanari *et al*., 1990; Niu *et al*., 1995; Niu *et al*., 2002). They can also provide other benefits. For example, as the air flow rate of these systems is less than that in conventional HVAC systems, the size of ductworks and air handling units can be smaller (Trane, 2009). Also, the systems can handle large sensible cooling load with relatively low sound levels; a quiet indoor environment can be achieved (Alexander and O'Rourke, 2008). Moreover, using this type of systems may help building owners get credit points in green building rating and certification, such as using the LEED (Leadership in Energy and Environmental Design) system (Mumma, 2001).

However, chilled ceiling systems are relatively new in Hong Kong and other locations with hot and humid climates. In order to assess their potential benefits on thermal comfort and energy performance, this research studied the basic principles and key characteristics of chilled ceiling systems through theoretical evaluation. Field studies in two pilot projects in Hong Kong were carried out to investigate the system performance and major considerations in practical applications. Building energy simulation is applied to assess the potential energy saving benefits of using chilled ceiling systems. It is hoped that a better understanding of the systems can be developed for promoting higher quality and better energy efficiency in HVAC design.

2. PRINCIPLES OF CHILLED CEILING SYSTEMS

Chilled ceiling system is a water-based cooling system which uses ceiling-based radiant cooling panels coupled with chilled water pipes or coils (Dieckmann and Brodrick, 2004). The chilled water pipes are laid behind metal false ceiling panels (ASHRAE, 2008). Figure 1 shows examples of the panels. The system cools the room by a combination of natural convection and radiation (Castillo and Tovar, 2012; Diaz, 2011). As radiation is the main heat transfer mechanism for chilled ceilings, the system is also known as "radiant chilled ceiling system" and "radiant ceiling panel system".

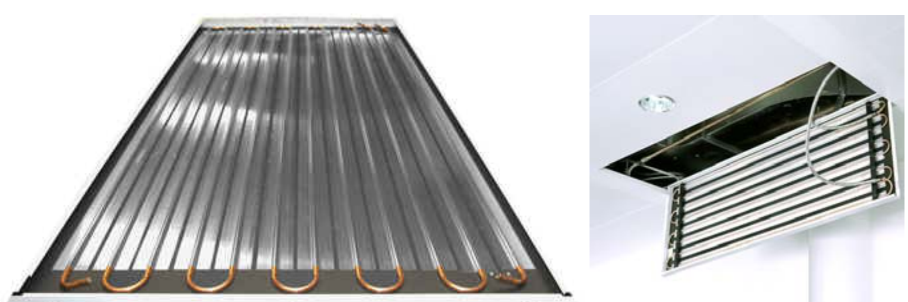

Figure 1. Examples of chilled ceiling panels
(Source of images: www.kuehldecken.de and www.sasint.co.uk)

Chilled water with a temperature around 14-17 ºC flows through the pipe system, thus the surface temperature of the ceiling panel is a few degrees below room temperature. All warmer surfaces like walls and windows, emanating equipment and people, dispense heat to the cold ceiling. When heat is absorbed, temperature of chilled water flowing through the nearest pipes rises about 2-3 ºC. Warm water is then piped out of the space and replaced by chilled water with original temperature.

In order to handle condensation problem on the ceiling panels, a separate dedicated outdoor air system (DOAS) is designed with chilled ceilings (Mumma, 2001). This ventilation makeup air system is used to dehumidify the outdoor air before entering the space through ventilation makeup air supply duct. As a result, the dew point of indoor air can be maintained lower than the temperature of ceiling panels. Figure 2 illustrates the operating principles of typical chilled ceiling systems. In fact, chilled ceiling systems separate the sensible part of cooling to ensure air quality and humidity control. The air distribution system is used to fulfill the ventilation requirements, and the water distribution system provides thermal conditioning to the building. DOAS must be designed to take out all the latent loads (might also remove 10 to 15% of sensible loads in the office space).

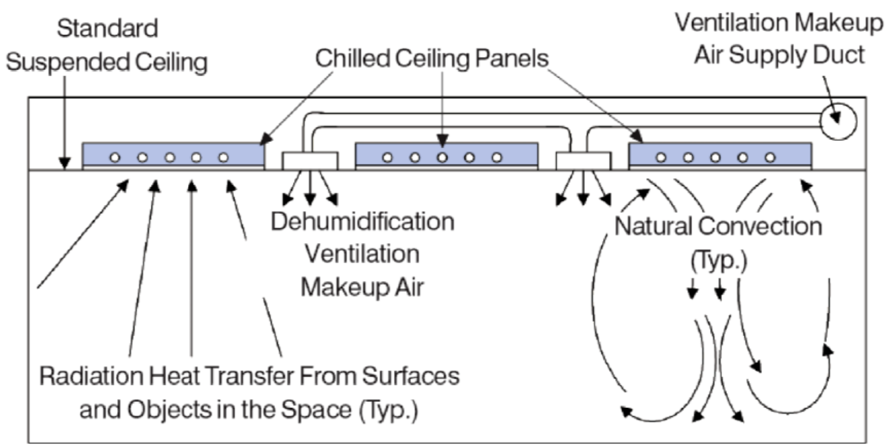

Figure 2. Operating principle of chilled ceiling systems (Dieckmann and Brodrick, 2004)

3. THERMAL COMFORT AND ENGERY PERFORMANCE

By combing convection and radiation, chilled ceiling systems could enhance human thermal comfort and reduce energy use in air-conditioned buildings (Diaz and Cuevas, 2011). As radiation accounts for a large proportion of heat removal by chilled ceilings, the system can operate at relatively small temperature differences between the room air and the chilled ceiling surface.

3.1 Thermal Comfort

Chilled ceiling systems can achieve better thermal comfort as compared with conventional HVAC systems (Catalina *et al.*, 2009). Based on the experimental studies (Imanari *et al.*,1990), the number of votes for thermal comfort under radiant ceiling panel system was more than the votes for conventional all-air system. At the same time, local thermal comfort is also improved. Supply air flow rate is lower because radiant ceiling panels deal with a major portion of sensible thermal load. Hence, the results of draft are reduced. In addition, Kitagawa and et al (1990) reported that the thermal sensation vote can be enhanced becoming "neutral" due to small air movement created by radiant cooling ceiling system.

With sensible cooling separated from ventilation, ventilation can be provided as needed to satisfy ventilation requirements (on a prescribed basis, or as determined by demand-control CO_2 sensors). Chilled ceilings always operate directly to the heat sources in a room (radiation), as well as to the quality of the indoor air (convection). The chilled ceiling cooling load is dissipated from the room by radiation. Exceeding allowable air velocities is not possible with this system; thus an unpleasant air draft, which arises with a usual air conditioning, does not occurs with the use of chilled ceilings.

The operative temperature is often used to indicate thermal comfort and it is composed of the mean surface temperature of the enclosed components of a room and the indoor air temperature. By the use of chilled ceilings the surface temperature of the ceiling (radiant temperature) is slightly lowered as the air temperature. Thus the indoor air temperature can be selected up to 3 ºC higher as the temperature of an only air system with the same perceived temperature. This will help decrease building cooling loads and energy use.

3.2 Energy Performance

Energy can be saved if chilled ceiling systems are applied. One of the basic energy savings mechanisms is the ability to operate with higher chilled water temperature, allowing the chiller evaporator temperature to be correspondingly higher. Niu *et al*. (2002) suggested that radiant ceiling systems are able to decrease air volume flow rate and increase evaporating temperatures. As a result, much fan energy and chiller energy can be saved. Another reason is the mode of heat transfer. Some ceiling radiant cooling panels are designed for radiation combined with mixed convective condition including both natural convection and forced convection. According to Jeong, and Mumma (2007), over 17% of cooling capacity can be enhanced under the mixed convention condition and radiation.

Nevertheless, some suitable measures should be carried out in order to achieve better energy performance effectively. Niu *et al*. (1995) stated two strategies to save energy. One is using water through the ceiling panels to pre- and re- heat the ventilation air. The other one is by-passing the chiller whenever possible to maximize evaporative cooling possibilities.

As noted earlier, chilled ceiling systems in most climates require installation with a DOAS to manage outdoor humidity. Together, the DOAS with chilled ceilings saves energy by reducing air moving power, reducing total ventilation air flow and by handling sensible cooling loads more efficiently. Air moving power is reduced because the only air moved is that required for ventilation (often only 20% to 30% of the normal all-air system air flow rates). This can also result in the reduction of ductwork dimensions, fan size and related resources.

4. FIELD STUDIES

Thermal comfort under chilled ceiling systems were evaluated by field studies in two pilot projects in Hong Kong, namely the offices of an aircraft engineering company and the site office of a construction company. For each area, thermal comfort parameters were measured for one week during October 2011. At the same time, occupants in both offices were invited to complete questionnaires about thermal perception. Hence, the predicted and subjective thermal sensations of occupants could be evaluated.

Using data loggers and portable instruments, the following parameters were measured: dry-bulb temperature, wet-bulb temperature, globe temperature (for determining mean radiant temperature) and air velocity. Based on on-site observation and judgment, assumptions of clothing value and metabolic rate were made. Clothing value is assumed 0.61 clo as most of the occupants were wearing long-sleeve shirt and trousers. Metabolic rate is assumed 1.1 met as most of the occupants were having office activities.

Using the approach in thermal comfort standards (ASHRAE, 2010; ISO, 1995) and the average value of the measured parameters, the thermal comfort indices including operative temperature, predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) were calculated. Key results are explained in the following sections. Moreover, in order to evaluate the subjective feeling of occupants under the chilled ceiling system, questionnaire was set and distributed to them. The questionnaire consists of four main sections: background of occupants, comfort perception, overall satisfaction and system evaluation.

4.1 Offices of An Aircraft Engineering Company

This company is located on Lantau Island near the Hong Kong International Airport. Two of their offices have been changed and started to use chilled ceiling system in 2011 (up to October 2011, this new system has been run for several months). One office is located in Hanger 1 while another office is located in Hanger 3. For the office in Hanger 1, only half of the office area was in operation; another half was still under construction. Thus, the office located in Hanger 3A East Annex 2/F was selected to work out the measurement. The area of this office is around 850m^2 with nearly 60 staff. Figure 3 shows an infra-red photo of the chilled ceiling in that office (the chilled ceiling has a surface temperature around 21-22 ºC).

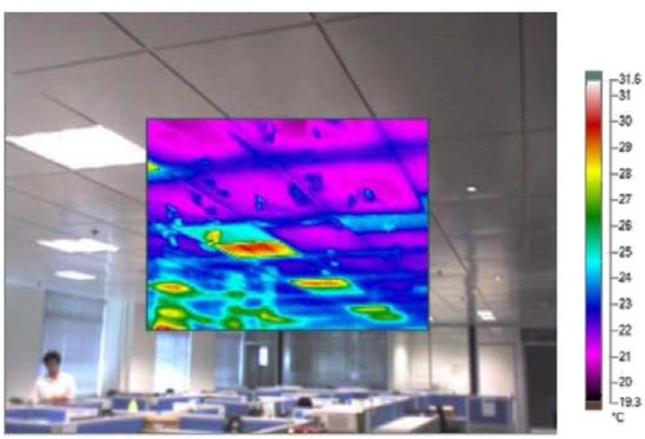

Figure 3. Infra-red photo of the chilled ceiling system in the company office

Table 1 gives a summary of the thermal comfort parameters for the company office. During the measurement, this office is divided into two zones (interior and perimeter). The perimeter zone is located about 5 m from the external windows and walls. The measured data and thermal comfort parameters for one week have been investigated and the data for the lowest and highest operative temperatures are indicated in Table 1 for easy comparison. Figure 4 shows a graph of PMV vs PPD and the calculated results for the interior zone are plotted. It can be seen from Table 1 and Figure 2 that the indoor environment is comfortable since the PMV is within ±0.7 and PPD is within 16%.

Table 1. Thermal comfort parameters for the company office

	Interior zone		Perimeter zone	
	Lowest	Highest	Lowest	Highest
Input parameters:				
Dry-bulb temperature (ºC)	21.91	23.86	22.86	25.56
Relative humidity (%)	44.9	39.7	49.7	40.1
Air speed (m/s)	0.02	0.02	0.01	0.01
Mean radiant temperature (ºC)	22.89	23.8	22.09	24.01
Clothing (clo)	0.61	0.61	0.61	0.61
Metabolic rate (met)	1.1	1.1	1.1	1.1
Calculated results:				
Operative temperature (ºC)	22.4	23.83	22.48	24.79
PMV	-0.7	-0.3	-0.7	0
PPD	15.3	6.9	15.3	5

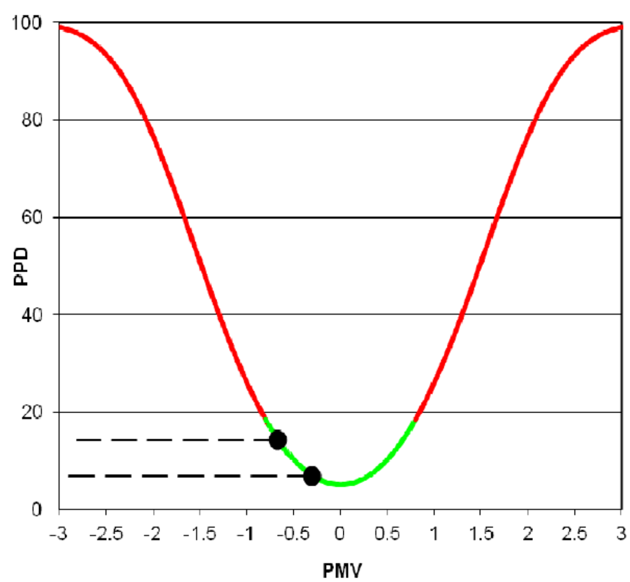

Figure 4. Calculated PMV and PPD results for the interior zone in the company office

For the survey questionnaire results, there are total 56 respondents. Generally, most of the occupants (84%) are satisfied with thermal sensation and only 16% are dissatisfied and feel the environment is hot, warm, cool or cold. For temperature, although only 14% are dissatisfied in temperature, 41% feel that the indoor sometimes is too hot. For air movement sensation, about 37% think that air movement is moderate, 51% of occupants feel that the air movement in office area is too low.

4.2 Construction Site Office

The site office is also located on Lantau Island and is designed for a cargo terminal project near the airport. The building has two storeys and the total floor area is around 700 m^2 with 65 staff. A chilled ceiling system is installed at the ground floor while a conventional HVAC system is used at the first floor. Thus, the field measurement was carried out only on the ground floor. The office is also divided into two zones (interior and perimeter).

The measured data and thermal comfort parameters for one week have been investigated and the data for the lowest and highest operative temperatures are indicated in Table 2. Figure 5 shows a graph of PMV vs PPD and the calculated results for the interior zone are plotted. It can be seen from Table 1 and Figure 2 that the indoor environment is still comfortable since the PMV is within ±0.8 and PPD is within 19%.

Table 2. Thermal comfort parameters for the construction site office

	Interior zone		Perimeter zone	
	Lowest	Highest	Lowest	Highest
Input parameters:				
Dry-bulb temperature (ºC)	21.99	23.63	22.48	24.79
Relative humidity (%)	45.5	37.8	50.7	35.7
Air speed (m/s)	0.02	0.02	0.01	0.01
Mean radiant temperature (ºC)	21.99	25.23	22.09	25.17
Clothing (clo)	0.61	0.61	0.61	0.61
Metabolic rate (met)	1.1	1.1	1.1	1.1
Calculated results:				
Operative temperature (ºC)	21.99	24.43	22.29	24.98
PMV	-0.8	-0.2	-0.7	0
PPD	18.5	5.8	15.3	5

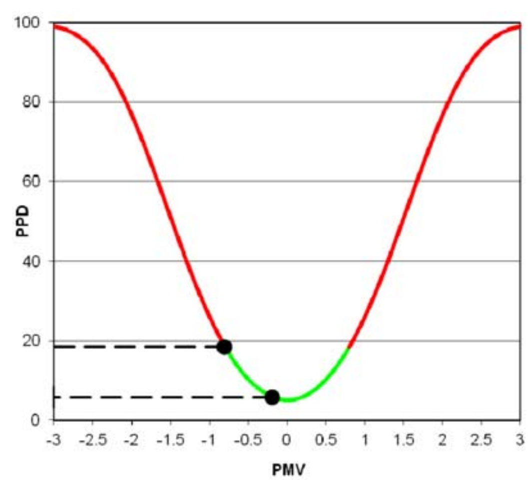

Figure 5. Calculated PMV and PPD results for the interior zone in the construction site office

For the survey questionnaire results, there are total 30 respondents. Generally, most of the occupants (80%) are satisfied with thermal sensation and only 20% are dissatisfied. For temperature, only 6% are dissatisfied and 27% feel that the indoor sometimes is too hot. For air movement sensation, 37% think that air movement is moderate, 40% of occupants feel that the air movement is too low.

5. BUILDING ENERGY SIMULATION

Building energy simulation is applied to assess the potential energy saving benefits of using chilled ceiling systems. A software VisualDOE 4.1 was used to evaluate the building energy performance. A hypothetical model for commercial buildings in Hong Kong was established based on a typical office building as described in Hui (2002). As no simulation software nowadays has suitable built-in functions for chilled ceiling systems, the analysis was developed by changing the characteristics of a variable air volume (VAV) system. Table 3 shows a summary of simulation results for the base case office building. It can be seen that the HVAC energy use including Cool (chiller plant and chilled water system) and Fans (for air handling units) constitutes 61% of total annual building energy consumption.

Table 3. Summary of simulation results for the base case office building

Annual energy:	Cool	Fans	Lights	Equipment	Total
MWh	6370	2945	3699	2254	15268
Percent	41.7%	19.3%	24.2%	14.8%	100%

Total building gross floor area = 49,939 m^2; Energy utilitisation index = 305 kWh/m^2

In order to assess the potential energy saving from the two major mechanisms described in section 3.2 (i.e. higher chilled water temperature and reduced air volume flow rate), two modified cases were developed from the base case model by changing the chilled water temperature setting and supply air flow rate. Table 4 gives a summary of the estimated energy savings for the two modified cases. The percentages of energy saving for each component (Cool 5.8%; Fans 50%), the HVAC system (19.8%) and the whole building (12.1%) are also calculated.

Table 4. Estimated energy savings for the two modified cases

Annual energy:	Cool	Fans
Base case [A]	6370 MWh	2945 MWh
Modified case [B] (description)	5998 MWh (Chilled water temp. increased from 6.7 ºC to 10.6 ºC)	1473 MWh (Supply air flow rate reduced to 30% of full supply)
Energy saving [A – B]	372 MWh	1472 MWh
Percent of energy saving	5.8%	50%

Total energy saving = 372 + 1472 = 1844 MWh
% of energy saving for HVAC (Cool + Fans) = 1844 / (6370 + 2945) = 19.8%
% of energy saving for whole building = 1844 / 15268 = 12.1%

Another factor affecting the energy saving is the selection of indoor design temperature (up to 3 ºC higher than conventional HVAC systems without compromising thermal sensation). According to a previous research on sensitivity analysis of the energy performance of office buildings in Hong Kong (Lam and Hui, 1996), the potential energy saving for 3 ºC increase of indoor temperature would be about 11% for the whole office building. The actual amount will depend on the operation schedule and temperature control.

6. DISCUSSIONS

From the findings of the field studies (Tables 1 and 2), it can be seen that the calculated results of PMV/PPD are quite close to the thermal sensation votes of the questionnaire. In both locations (company office and construction site office), the PMV values obtained from the field studies are on the slightly negative side (-0.2 to -0.8). This implies that the indoor air temperature (21.9 ºC to 25.6 ºC) could be increased a bit to bring PMV to zero (neutral) and this temperature increase could reduce further the cooling load and energy use.

One aspect of thermal comfort which was not verified in the field studies is the possible local discomfort due to vertical radiant temperature asymmetry because the chilled ceiling has a surface temperature lower than the floor and other surfaces. Hodder and et al (1998) pointed out that vertical radiant temperature asymmetry have an insignificant effect on the overall thermal comfort of the seated occupants for the typical range of ceiling temperature (see an example in Figure 3). As normal office spaces have a typical floor-to-ceiling height of 2.5 to 3 m, it is believed that the chilled ceiling system can still avoid local cool sensation for a vertical radiant temperature asymmetry of up to 14 ºC.

6.1 Air Movement

Findings from the field studies indicate that although most occupants are satisfied with the general indoor environment, some occupants feel that the air movement is sometimes too low. It was also observed that a few office staff had small portable fans on their desks which can be used to promote air movement. Although the low air movement of chilled ceiling systems can help enhance the thermal comfort sensation and avoid draft (excessive air velocity), attention must be taken to prevent stagnant air situation when natural convection is not adequate to generate the minimum air movement.

Kitagawa and et al (1990) have studied and discussed the effect of humidity and small air movement on thermal comfort under a radiant cooling ceiling. They found out that small air movement, especially including velocity change, had a tendency of improving the comfortable sensation vote near neutral thermal sensation, however, reducing the comfortable sensation vote in the cooler conditions whose thermal sensation vote was less than -1. The most comfortable sensation vote was obtained in the condition whose thermal sensation vote was not neutral but approximately -0.5. This is similar to the findings of our field studies.

6.2 System Design and Heat Transfer

Diaz (2011) pointed out that the hydronic ceiling system must be evaluated together with its designed environment (walls, ventilated facade, internal loads and ventilation system). The cooling power of a chilled ceiling system depends on the heat transfer (convection and radiation) between the room walls, air and the ceiling. The convective heat transfer is a function of the air velocity and direction at the ceiling level and the location of the air inlets and panel perforations effect, which in turn depends on the room and diffusers geometry, the location and power of the internal heat sources and interaction with the heated or cooled facade. The radiation heat transfer must be calculated from the room geometry and room surface characteristics of the ceiling, walls, facade and specially their interaction.

The importance of the radiant transfer component suggests that more emphasis should be placed on this aspect during the system design (Hirayama and Batty, 1999). In general, chilled ceiling systems provide large surface areas for radiant cooling. In order to handle the indoor heat sources effectively, the heat transfer potential between the building components and the interior space should be considered carefully. Castillo and Tovar (2012) have developed a theoretical model to study the heat transfer of a chilled ceiling at transient and equilibrium conditions. They found that the dominant flow was the Rayleigh-Bénard convection produced from the ceiling and this flow cancelled out the thermal stratification produced by the heat source on the floor (from displacement ventilation). It implies that chilled ceiling systems can effectively manage the turbulent thermal plumes and achieve reasonable air flow patterns if designed properly (Taki and et al, 2011).

6.3 Hot and Humid Climates

When chilled ceiling systems are applied in hot and humid climates, the biggest challenge is the precise humidity control to avoid condensation (Ge *et al*., 2012). Condensation control is important for these systems, especially in buildings with natural or hybrid ventilation, an "unoccupied" set back schedule on nights and weekends, or transient latent loads (e.g. extra occupants). Shou and He (2012) have analyzed the condensation process in radiant cooling system and proposed the concept of dehumidification capacity per unit mass of fresh air to be the basic index to judge whether radiant cooling system should be used. Zhang and Niu (2003) indicated that dehumidification and ventilation prior to cooling panels operation is required to reduce condensation risks in hot and humid climates; a one-hour in advance dehumidification/ventilation in summer could completely eliminate the condensation problems. If dehumidification of the air mass in the space is really needed, a chilled radiator system (not on ceiling) might be applied at strategic locations in relationship to the fresh air inlets and the occupants (Hirayama and Batty, 1999).

To avoid condensation of moisture on the chilled ceiling panel, the temperature of water supplied to the panel and thus cooling capacity per panel area were limited (Vangtook and Chirarattananon, 2006). But this also offers good opportunity for energy conservation as low energy methods can be used to reduce chilled water temperature to the required level. For example, there is an added benefit of extending the operating range of the water-side economizer where cooling water is obtained through passive means from the evaporative cooling towers (Facão and Oliveira, 2000).

6.4 Integration with Other HVAC Technologies

To further improve the thermal comfort, indoor air quality and energy efficiency, other HVAC technologies can be integrated or combined with the chilled ceiling systems. For instance, displacement ventilation, desiccant dehumidification and total heat recovery have been adopted and evaluated in some research (Chakroun *et al*., 2011; Ge *et al*., 2011; Hao, *et al.*, 2007; Niu *et al*., 2002; Novoselac and Srebric, 2002). These technologies and the chilled ceiling systems can complement each other to achieve better system performance and minimize total energy consumption.

As mentioned earlier, since chilled ceiling systems operate with relatively high chilled water temperatures (around 14 °C to 17 °C) they may make use of the low exergy (Wang *et al*., 2008) and free cooling alternatives to mechanical refrigeration, such as ground water cooling, thermosyphon cooling and evaporative cooling (Alamdari *et al*., 1998). This has the potential to reduce the energy consumption in cooling season and decrease the CO_2 emissions associated with the building cooling system.

7. CONCLUSIONS

Chilled ceiling systems have the potential to enhance thermal comfort, improve indoor air quality and reduce energy use in air-conditioned buildings. The operating principles of these systems and the relevant research information on thermal comfort and energy performance have been studied to form the theoretical evaluation. Also, field studies in two pilot projects in Hong Kong were carried out to investigate the system performance and practical considerations. It is found that by combing convection and radiation, chilled ceiling systems can enhance thermal comfort and reduce HVAC energy use. Moreover, these systems separate the sensible part of cooling from ventilation to ensure effective control of air quality and humidity in the air-conditioned space.

Findings from the field studies indicate that most occupants are satisfied with the general indoor environment under the chilled ceiling; the calculated results of PMV/PPD are quite close to the thermal sensation votes of the questionnaire. It is also noted that the indoor air temperature could be increased a bit to bring PMV to neutral and reduce further the cooling load and energy use. Some occupants feel that the air movement is sometimes too low; attention must be taken to prevent stagnant air situation.

The results of building energy simulation show that the fan energy saving is the most important component and the percentages of energy saving for the HVAC system (19.8%) and the whole building (12.1%) are significant. The high temperature cooling of chilled ceilings can maximize the opportunity for free cooling and other low-energy cooling methods, which is good news for sustainability and green building design. Further research is needed to assess the applicability and effectiveness of chilled ceiling systems in retrofit, renovation and new construction projects for different types of buildings.

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