A COMPARISON OF INDOOR HUMIDITY BEHAVIORS: ALL-AIR AND CHILLED-CEILING WITH DESICCANT COOLING

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ABSTRACT
Indoor humidity behaviors with a system combining chilled-ceiling and desiccant cooling (CC+DC) in hot and humid climates are investigated and compared with a conventional constant volume all-air system (CAV). Room mean temperature, mean humidity, maximum RH on the ceiling panel surfaces, annual condensation hours are predicted using a building energy simulation code ACCURACY and a moisture balance analysis method in an office room under Hong Kong weather conditions. The results show that the system controls the indoor humidity poorly in transient seasons, but in comparison, the CC+DC system provides better indoor humidity environment most of the year. For CC+DC, air dehumidification and ventilation system should be operated at least one hour earlier than the operation of ceiling panels. Otherwise, condensation may occur.

INDEX TERMS
Radiant cooling, Humidity, Desiccant cooling, Condensation

INTRODUCTION
There have been increased interests of radiant cooling in North America and Asian countries due to its inherent advantages of increased thermal comfort with reduced energy use (Feustel and Stetiu, 1995; Stetiu 1992; Niu, Kooi Ree 1995). However, up until now, most of the works concerning radiant cooling are focused on its thermal analysis, while indoor humidity, which is equally important as thermal performance, is neglected. The scarcity of knowledge in this area has limited the applications of chilled-ceiling systems to hot and humid regions, where the risk of condensation on the chilled ceiling surfaces represents a significant problem. This is understandable considering Hong Kong has a hot and humid summer with an average dew point exceeding 22°C. Consequently, indoor moisture levels need to be carefully controlled in this climate, not only for thermal comfort purposes, but also for condensation reasons. It is inevitable that air dehumidification and ventilation must be well combined with chilled ceiling panels and the resulting indoor humidity performance should be evaluated, in addition to building thermal performance analysis.

In this paper, the indoor humidity behaviors associated with a system combining chilled-ceiling and desiccant cooling (CC+DC) are investigated and compared with a traditional constant volume all-air system (CAV). Some operational measures to prevent water condensations on ceiling panels are recommended.

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SYSTEM DESCRIPTIONS
Traditional air-conditioning system is constant volume all-air system. In such a system, both the sensible and latent load is treated by coiling coils in an AHU (Air Handling Units). To use the concept of radiant cooling, a new system, namely, a system combining chilled-ceiling with desiccant cooling, is proposed, as shown in Fig.1 for schematics and Fig.2 for psychrometrics, respectively. With this system, the latent load is treated by the desiccant cooling system and most of the sensible load is treated by ceiling panels. The water flow rate to ceiling panels is kept fixed, while the inlet water temperature is controlled instead to maintain a pre-fixed indoor environment.

Figure 1. Schematics of the system combining chilled-ceiling with desiccant cooling.

Figure 2. Psychrometrics of air handling in desiccant cooling.

The main purpose of desiccant cooling is for fresh air ventilation and dehumidification. Ambient outdoor air at state 1 enters the supply air duct. This air passes through a desiccant wheel and hot, dry air exits at state 2. This increase in temperature is due to the heat of
sorption and some sensible heat transfer. The hot, dry supply air transfers much of this heat to the return air stream in process 2 to 3 involving a sensible heat wheel. Unlike a commonly used desiccant cooling, where air at state 3 is evaporatively cooled to state 4, in this system, the warm, dry air at state 3 is cooled by a cooling coil to around 18°C, to keep the dryness of supply air at state 4. The cool, dry air at state 4 is then distributed to the room. After accepting the building latent load and a small amount of sensible load, the air then returns to the desiccant system through return air ducting. This is the state of the air which corresponds to state 5. This somewhat cool, fairly dry air is evaporatively cooled to as low a temperature as possible at state 6. This cold, damp air is then preheated by the rotary sensible wheel to state 7 while cooling the supply air stream. State 7 is the state of the moist air as it enters the heating coil. Hot, humid air exits at state 8 and regenerates the desiccant wheel. Warm, very humid air at state 9 is then exhausted to the surroundings. In this combined system, an evaporating temperature as high as 15°C is needed for the water-chiller, which means a much raised COP.

**METHODS**

Thermal performance is evaluated by a special cooling load program for cooled ceiling systems ACCURACY (Niu and Kooi 1994) which is developed and validated previously at Delft University of Technology in Netherlands. The program calculates not only the cooling load, but also the required supply water or air temperatures for different panel installation areas. The program also works out the respective convective and radiant heat extractions by cooling panels, and the radiant and convective heat from all the window and wall surfaces. Adopting such building dynamics simulation techniques, year round simulation of rooms with or without chilled-ceilings provides hour-by-hour data of cooling/heating loads, and temperatures of room air and other components.

Moisture balance in the room is calculated by,

\[
\frac{V_r \rho_r \frac{d\bar{w}}{d\tau}}{\bar{v}_s} = -\bar{v}_s \rho_s (w_s - \bar{w}) + ACH \cdot V_r \rho_o (w_o - \bar{w}) + \dot{m}_s - \dot{m}_{ad/de} \tag{1}
\]

where \(V_r\) is the room volume (m\(^3\)), \(\rho\) is air density (kg/m\(^3\)), \(w\) is humidity ratio (kg/kg), \(\tau\) is time (hr), \(\bar{v}_s\) is supply air volumetric flow rate (m\(^3\)/h), \(ACH\) is air infiltration rate (h\(^{-1}\)), \(\dot{m}_s\) is indoor moisture generation rate (kg/h), subscripts “r”, “o”, “s” refer to “room”, “outside”, and “supply” respectively. The last term \(\dot{m}_{ad/de}\) is moisture adsorption and absorption by room surfaces and furniture (kg/h). In general, the moisture adsorption/absorption properties of building materials are less understood, therefore, overall, precision of moisture prediction lags behind that for thermal prediction. In this study, the indoor surface and furniture adsorption and desorption effects are not included. In reality, such effects may help smooth the RH fluctuations, but will not significantly affect the hourly averages (Niu and Burnett 1998). In simulations, thermal analysis is coupled with moisture analysis to take into account the interactions between thermal and moisture performance. The performance of the desiccant cooling system is predicted with a model proposed by (Jurinak, Mitchell, and Beckman 1983)

A typical office room in a south-facing high-rise building in Hong Kong (22°N, 114°E) is simulated in this study. The office is 5.1m long, 3.6m wide, and 2.6m high. The thickness of the envelope is 260mm and the resulting heat transmission coefficient \(U\) for the opaque part of the facade is 2.91W/m\(^2\)K. The glazing area is 2.88m\(^2\) with double-pane windows of which center-of-glass \(U\) value is 1.31 W/m\(^2\)K. Louver curtain is installed behind windows. It is determined that about 70% of the ceiling is covered by radiant ceiling panels when the radiant
ceiling panel system is applied. An occupancy pattern of 2 persons with a schedule from 9 to 18h is simulated in the office. When present, each person generates 75W sensible heat and 57.6g/h moisture. Of the sensible heat generated, 50W is radiative and 25W is convective. Besides, constant loads of 459W of equipment and lighting with a schedule from 9 to 18h are modeled in the room. Half of these loads are considered as radiative and half convective. The operating hours of the ceiling panels and ventilation systems are also from 9 to 18h. However, as will be discussed later, dehumidification/ventilation prior to the operation of chilled-ceilings would be required in summer to prevent condensation on panel surfaces. Air infiltration rates ranging from 0.05 to 0.4 ACH are modeled during the time when the ventilation system was switched off and the building is not pressurized.

The supplied chilled water flow rate to the ceiling panels is 0.5t/h, resulting a temperature rise of about 1.6°C through the panels. The ventilation fresh air is supplied at a rate of 67m³/h, which complies with ASHRAE standard 62 (ASHRAE 1999). For all-air systems, the ratio of return/fresh air is 3.4, resulting a supply air flow rate of 300m³/h. The operative temperature is set to 25°C in summer and 23°C in winter.

RESULTS AND DISCUSSION
The distribution of indoor relative humidity during working hours are shown in Fig.3 for CAV and CC+DC. The optimum zone is from 40% to 60%RH and 50% RH is ideal for building occupants to avoid the hazards of fungi, bacteria, viruses, and respiratory difficulties. The figure shows that the all-air system has the least annual hours in the comfort region, and has the most hours in either the dry (<40%) or the humid (>60%) regions. The chilled-ceiling combined with desiccant cooling controls the indoor humidity best: 90% of annual operating hours is in the optimum region.

The monthly averaged relative humidity is illustrated in Fig.4 for CAV and CC+DC. For conventional constant volume all air system, the minimum RH is in July and the RHs are well controlled to around 50% in summer season. In winter and transient seasons, the RHs rise up. RHs higher than 70% occasionally occur in these seasons. This phenomenon is due to the fact that in a conventional all air system, temperature is intentionally controlled, while the humidity is passively controlled, because the supply air state is determined by the sensible load. In winter and transient seasons, sensible load becomes smaller and air is not sufficiently dehumidified. The result of this approach is a loss of humidity control while the temperature is maintained at setpoint. In contrast, in a CC+DC system, both the temperature and the indoor humidity are well controlled around set points, since they are decoupled and intentionally controlled independently. The variations of monthly averaged RH are relatively small and they are in phase with outside humidity fluctuations: maximum in August and minimum in February. It can be concluded that chilled-ceiling systems have better indoor humidity controls with reduced energy use than their all-air counterparts.

Even though chilled-ceiling systems realize independent humidity control with reduced energy use, when used in hot and humid regions, condensation on ceiling panels remains a troublesome issue. To prevent condensation, room air needs to be dehumidified prior to the operation of ceiling panels. A one-hour in advance dehumidification/ventilation strategy is simulated in which ceiling panels are operated from 9:00-18:00 and the AHU is operated from 8:00-18:00. The room moisture levels are substantially pulled down during the first dehumidification hour, and when the ceiling panels begin to operate, the maximum RHs are below 90%. Therefore, water condensation is prevented. The larger the air infiltration rates at night, the earlier it requires for air dehumidification, to prevent condensation. Generally
speaking, a one hour in advance dehumidification could prevent condensation for most buildings except those that have very high air infiltration rates. On the other hand, if a building is well enclosed and the air infiltration rate is less than 0.05 at night, no condensation occurs even for simultaneous dehumidification and ceiling cooling. The condensations with desiccant cooling are similar to those with AHU.

![Figure 3](image-url)

**Figure 3.** Indoor humidity distributions of two systems: CAV and CC+DC.

![Figure 4](image-url)

**Figure 4.** Monthly averaged relative humidity: CAV and CC +DC

**CONCLUSIONS**

The conventional constant volume all air system passively controls the indoor humidity. The result of this approach is a loss of humidity control while the temperature is maintained at set point in transient seasons. In contrast, in a system combining chilled-ceiling with air dehumidification, the temperature and the indoor humidity are decoupled and intentionally controlled independently. As a result, more annual hours are in the comfort region.

Air dehumidification and ventilation system should be operated at least one hour earlier than the operation of ceiling panels. Otherwise, condensation may occur. However, if a building is
well sealed and the air infiltration rate is less than 0.05 at night, no condensation occurs even without in advance dehumidification.

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REFERENCES


