Low Temperature Radiant Cooling Design and Application in Tropical/ Sub-Tropical Countries

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ABSTRACT

Radiant cooling design has been practiced in many countries in the form of chilled beams or chilled ceiling and intakes chilled water temperature at around 16°C to avoid condensation under normal indoor conditions. With such 'high temperature 'radiant cooling equipment, it cannot meet the high cooling load requirements for tropical/sub-tropical countries like Hong Kong making this cooling design not popular in these countries.

Currently with the new emerging technology, a new breed of 'low temperature' radiant cooling products are now available in the market where intake chilled water temperature can be as low as 7°C without condensation problem when working with a special fresh air system. Indoor Environmental Quality (IEQ) is also much enhanced due to it's silent operation, capable of providing full fresh air to the indoor space, no draft and evenness of temperature distribution.

With this 'low temperature' design, performance of these radiant cooling products is greatly enhanced to meet cooling demand for hot and humid countries like Hong Kong. Cooling energy saving can be up to 40 % reduction compared to conventional convective air-conditioning design. Fan and pump power can also be greatly reduced since it is basically a passive system with much reduced chilled water flow rate.

This paper will discuss the design, energy performance, indoor Environmental Quality, E&M spatial advantages, cost, maintenance requirements and applications/ limitations of this range of 'low temperature' radiant cooling system compared to conventional AC design.

Keywords: *adaptable design, energy saving, indoor environmental quality*

1. CONVENTIONAL AC DESIGN

Heat transfer can be in the form of conduction, convection, radiation or a combination of all the three forms. In conventional air conditioning design, convection process has generally been adopted in that the air conditioning system absorbs heat by convection or circulating cool air in an indoor space. The cool air rises while it absorbs heat and returns through air ducts or plenum back to the cooling coils of the AC equipment where it is cooled down again before being re-circulated back to the space to repeat the cooling process.

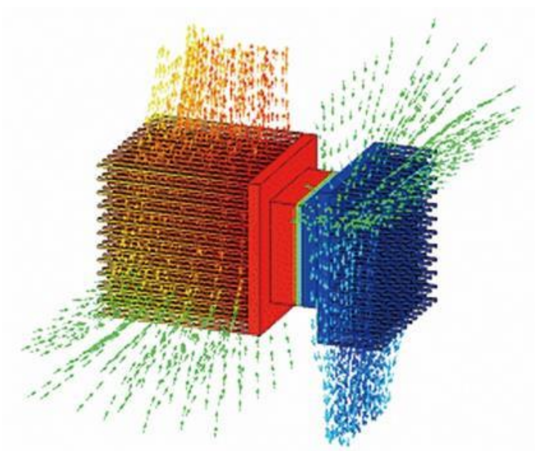


Figure 1: Convection air conditioning design

This convective heat transfer process uses the following equation:

$$Q = h \cdot A \cdot (Ts - Tf)$$

Equation 1

In conventional AC design the heat transfer between different fluids is more commonly expressed as:

$$Q = \dot{m}\,Cp \cdot (T1 - T2)$$

Where, Q = heat transferred per unit time; hc = convective heat transfer coefficient; A = heat-transfer area of the surface; Ts = temperature of the surface; and Tf , T2 = temperature of the fluid, $\dot{m}$ is the mass flow rate of the fluid, Cp is the heat capacity of the fluid.

Equation 2

This conventional AC design basically mixes cool supply air with the indoor air to form a cool reservoir of air where heat is absorbed and removed by the cooling process as mentioned above. Since invented by the famous American Dr Willis H Carrier more than 100 years ago, this AC design has widely been adopted by engineers and designers. However, nowadays with increasing demand of better IEQ and conservation of energy, the following disadvantages of this kind of convective AC design attract more and more comments:

- Over 80 % of indoor air has to be re-circulated that means odour, suspended dust particles, air contaminants, bacteria, virus, etc. will also be re-circulated back to the indoor space that deteriorate the air quality or put more reliance on air filter performances/ maintenance hence increasing life cycle cost;
- Air is a poor conductor and the whole indoor space has to be cooled down making this AC design method inherently energy inefficient;
- Large fan power is required to re-circulate and treat the bulk volume of air in the space;
- Very often air draft, uneven distribution of air and temperature, fan/ air borne noise, water dripping are experienced that cause nuisance to occupants;
- Large air handling equipment and air ducts are involved that occupy valuable indoor space.

2. RADIANT COOLING PRINCIPLES AND DESIGN

Radiant cooling however does not depend on circulating cool air but rather it uses differences in surface temperature of objects to effect heat transfer. According to law of radiation, any object with surface temperature above 0-degree K will continuously radiate and absorb heat energy via electromagnetic wave to/ from surrounding in the speed of light.

The convective AC design will also cool down 'surfaces' of the indoor area that will enable 'radiant cooling' to take place but the effect is minimal as heat absorbed through this process is very slow and limited.

We should also note that the media in which this heat transfer process is taking place does not have a direct effect of the process. For example sun ray travels through vacuum and the very cold 'Outer Space' before reaching our body but we still feel the 'intense heat' of the sun. We feel the 'heat' because radiation heat transfer takes place via the difference in surface temperature of the sun (around 5800 K) and our body (around 306 K).

Hence with the application of radiant cooling for indoor space, condition of indoor air can be seen as 'transparent' or it's effect can be considered 'minimal' that gives this design much more rooms for indoor environmental quality (IEQ) control and energy performance improvements.

Radiant heat transfer equation:

$$\text{Stefan-Boltzmann law } Q = e \cdot \sigma \cdot A \cdot (Tr4 - Tc4)$$

where, Q = net radiated power; e = emissivity; σ = Stefan Boltzmann constant;

A = radiating area; Tr = temperature of the radiator; Tc = temperature of the surrounding

Equation 3

Emissivity for an ideal radiator (black body) has a value of 1.

Hence Q is proportional to the object surface area, emissivity and difference in surface temperature in the 4th order of power.

In radiant chilled ceiling design, metallic ceiling is preferred for more effective heat transfer. Chilled water temperature down to 7°C can be supplied to the cooling coil of the chilled ceiling panel to enable maximum evenness of ceiling surface temperature, more effective/ responsive performance under various load conditions. The following criteria and assumptions are adopted in this 'Low Temperature' chilled ceiling design:

- Supply chilled water temperature lowest is 7°C and chilled ceiling surface temperature to be maintained at 2 degree above dew point temperature of the indoor condition at all times (minimum ceiling surface temperature is 16°C)
- Indoor humidity shall be controlled at 55 % RH or below with fresh air at 11°C RH 100 % under an outdoor condition of 33°C RH 90 %
- Fresh air supply rate from 10 l/s per person to 20 l/s per person and indoor CO_2 concentration to be controlled below 800 ppm at all times
- Chilled ceiling area coverage from 40 % to 50 % depending on the building usage, population density, façade design, building orientation, and equipment load
- Fresh air will control the indoor humidity and CO_2 concentration through low pressure air ducts and variable speed drive PA fan unit. Chilled ceiling will handle most of the sensible heat loads including solar, equipment and people load.
- An air tightness test in accordance with CIBSE Technical Memoranda (TM23: 2000) should be carried out to ensure air tightness of the indoor environment

3. LOW TEMPERATURE CHILLED CEILING CONSTRUCTION AND INSTALLATION ARRANGEMENT

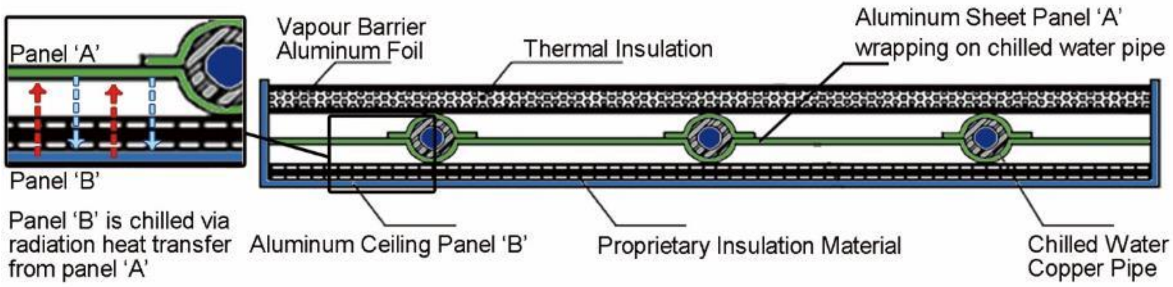


Figure 2: Radiant cooling panel construction detail

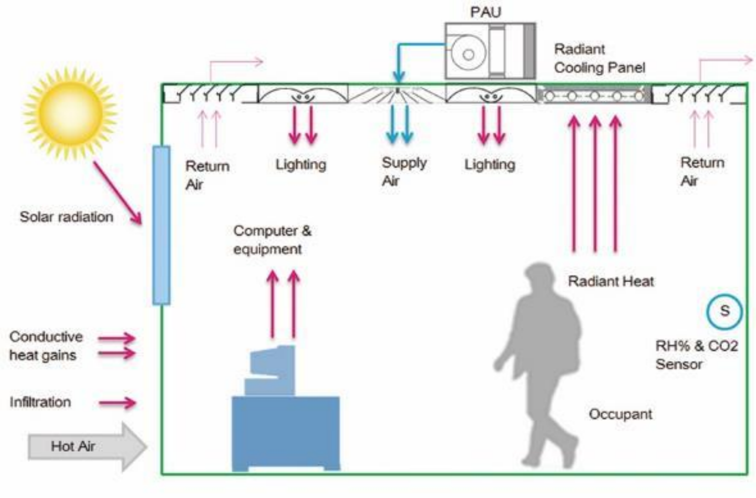


Figure 3: Cooling load components

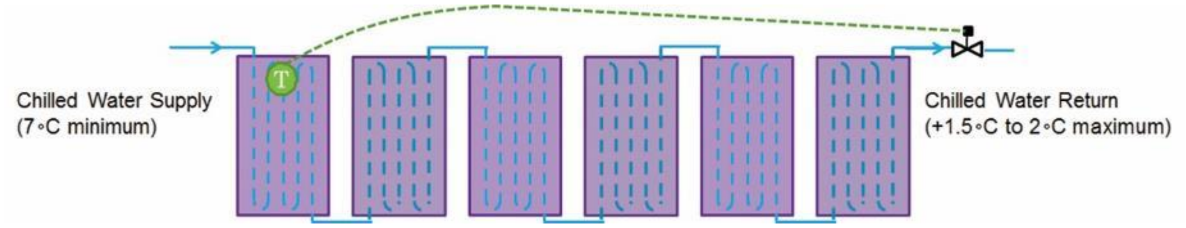


Figure 4: System connection for radiant cooling panels

4. CASE STUDY OF A LOW TEMPERATURE CHILLED CEILING PROJECT IN HONG KONG

This is an existing 30-storeys office building in Hong Kong that was being renovated into a modern office. The existing building constraints are that the floor to floor height is only 3000 mm with flat slab structure and there is no further space on roof to accommodate additional chillers and cooling towers to increase chiller loading.

The client is Hong Kong Hang Seng Bank and it's brief is to create a modern work place with flexibility in staff mobility, an excellent IEQ and low energy performance to achieve a minimum LEED 'Gold' certification, a finished ceiling height of 2400 mm and a raised floor for power and IT cablings.

The Total Gross Floor Area of the building is around 30000 m^2 with population density in future of up to110 persons / floor (about 7 m^2/ person). The existing façade is single glazed with tinted glass where shading coefficient and energy performance are only up to standards some 25 years ago. The existing chiller capacity is 1100 TR and to meet future cooling demand the chiller capacity has to be increased to around1600 TR using conventional fan coil system.

In view of the low existing floor height, conventional fan coil system can only achieve a maximum of 2200 mm finished ceiling height that is largely below client's expectation for this modern office. To meet client's brief and to overcome the site constraints, an innovative low temperature chilled ceiling design was proposed.

Figure 6: Existing structural ceiling level

Figure 7: Original office (Fan coil unit)

Figure 8: New office (Chilled ceiling)

4.1 Design of chilled ceiling and fresh air system

Figure 9 below shows a typical chilled ceiling (in pink colour) layout plan used both in open plan office and meeting rooms. The chilled ceiling panel sizes can be standard 600x600 mm or made in different dimensions and shapes to suit interior designer's requirements.

The system is designed into different chilled ceiling zones to meet different user's requirement. Independent temperature sensors and humidity sensors are installed to control the room IEQ conditions by modulating supply chilled water temperature/ flow rate and fresh air supply temperature/ quantities. Dew point temperature sensor is incorporated in the chilled panel to cut off chilled water supply to avoid condensation.

Figure 9: Typical ceiling plan

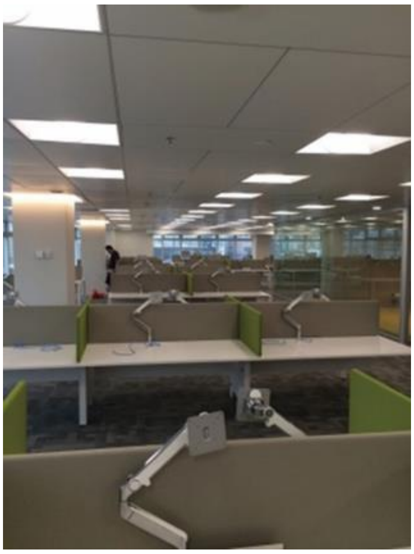


Figure 10: Open plan office


Figure 11: Meeting room

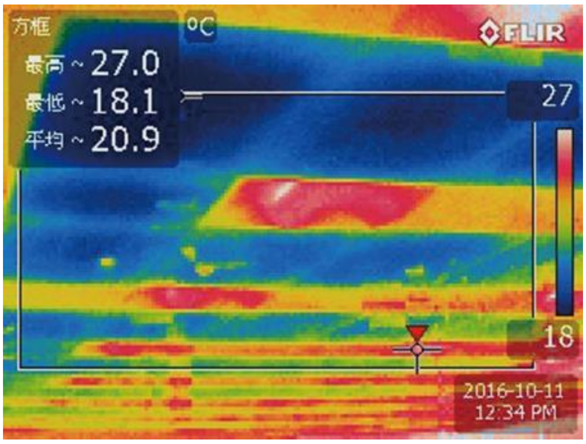


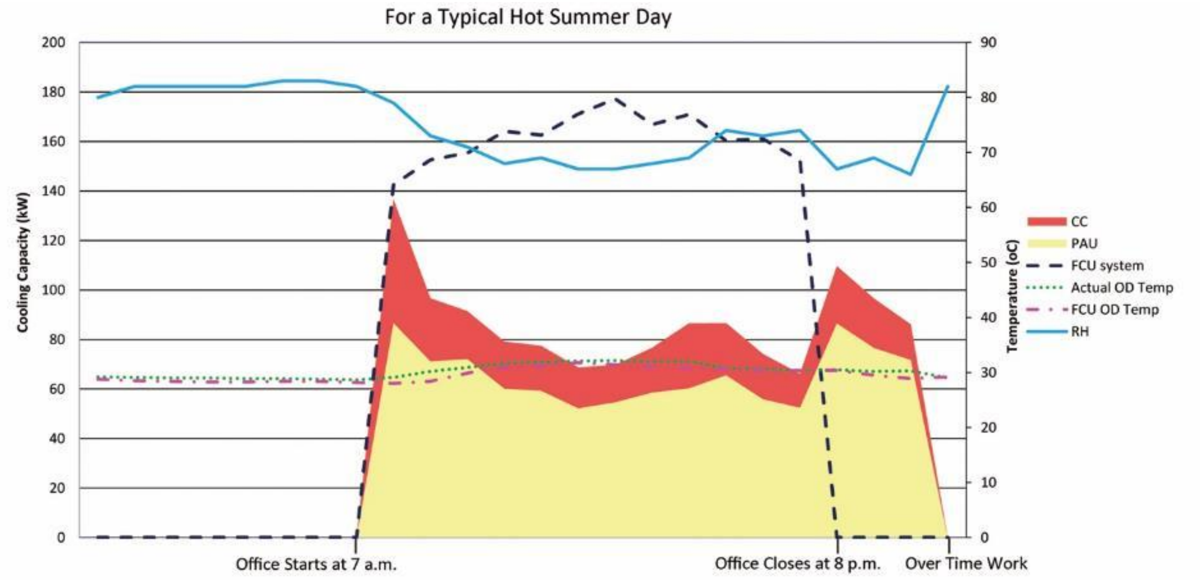
Figure 12: Thermal scan image of chilled ceiling

The above results show that performance of this chilled ceiling design can meet all requirements in the client's brief with satisfaction by most of the end users. Total chiller load is predicted to be around 900 TR upon full occupation such that additional chillers are not necessary to meet the new cooling load demand.

4.2 Merits of chilled ceiling versus conventional AC systems

	VAV/ AHU System	**Fan Coil System**	**Chilled Ceiling System**
1. IEQ			
• Space Temperature	23°C±1°C	23°C±1°C	23°C - 27°C
• Relative Humidity	55 % - 70 %	60 % - 75 %	50 % - 55 %
• Heating/ Cooling	Both but not common/ not well accepted	Both but not common/ not well accepted	Both and relatively comfortable so expected to be welcome by market
• **CO_2 Concentration**	**Average 900-1000 ppm**	**Average 1000-1400 ppm**	**Average 600 ppm**
• **Recirculation Air**	**80 %**	**80 to 90 %**	**Flexible and can be full fresh air**
• **Acoustic**	**Medium NC 38**	**Noisy NC 40 average**	**Extremely quiet typically under NC 30**
• **Air Draft Problem**	**Exist**	**Exist**	**Very Minimum**
• **Temperature uniformity**	**Average**	**Fluctuating**	**Very Even**
2. Energy Performance			
• Cooling Load	200 W/m^2	180 W/m^2	100 W/m^2
• Water Pump Power	'A' kW	'A' kW	0.75 x 'A' kW
• Air Fan Power	'B' kW	0.4 x 'B' kW	0.25 x 'B' kW
3. Operation and Maintenance			
• **Ease of Operation**	**Complicated**	**Less Complicated**	**Medium Complicated**
• **Maintenance Cost**	**High**	**High**	**Low**
4. Plant Spatial Requirement			
• **Requirement**	High	Medium	Low
5. Cost			
• **Capital Cost**	**High**	**Low**	**Medium (Due to limited suppliers)**
• **Running Cost**	**High**	**Medium**	**Low**

5. COOLING LOAD PROFILE



It is noted that the cooling load profile for a Chilled Ceiling System is a reverse of a conventional VAV or Fan Coil System that can significantly improve the electrical demand profile of a building.

6. LIMITATIONS

The following limitations of this radiant cooling design are observed:-

- Suppliers of proven products in the market are few resulting that initial cost is relatively high. There are limited design professionals in the trade so that this design technology cannot be proceeded on a large scale basis.
- Unfamiliarity by the end users on the system further deters development of this low energy cooling design in the market. To ease this problem perception of thermal comfort as elaborated in Ole Fanger's Predicted Mean Vote (PMV) index can be used to holistically review this system to confirm level of thermal comfort should achieve very high score to most people.
- Due to complexity of the indoor radiation cooling process, no formulated or validated calculation is available at present to verify cooling load calculation such that most parts of the design have to rely on past project data and references.
- New control strategy is adopted so that FM team needs to adapt and be trained to avoid operation problems like condensation.
- There may be higher water spill risk as more water pipes are installed but this problem can easily be resolved by specifying a reliable pipe connection system.

7. CONCLUSION

This innovative low temperature radiant cooling design can save up to 50 % of the cooling energy, 30 % of the pump power and 75 % of the fan power compared with conventional AC system. Furthermore the IEQ provided by this system can be much improved as confirmed in our case study project. It's application can almost cover all types of building including offices, hotel, hospitals, health care/ elderly centres, transportation facilities, airports, exhibition spaces, theatre, concert halls, factories and luxurious residence.

Following recent signatory of the two world most powerful countries - China and USA for the 'Paris Accord', energy conservation will regain top of the agenda of most developed/ developing countries for years ahead. It is hoped that with the continual development of the product and support from the market, this innovative low energy radiant cooling system can become the most promising design for indoor environmental control system of most building projects in the near future.