A simulation study of radiant chilled ceiling with dedicated outdoor air system for office buildings in Thailand

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Abstract. Radiant chilled ceiling (RCC) integrated with dedicated outdoor air system (DOAS) has been considered as a system offering building occupants a good thermal comfort with energy efficiency. This paper compares three different configurations of RCC and DOAS system in terms of cooling load, room condition and energy consumption. The results from TRNSYS simulation presented that all the configurations could maintain the indoor condition with the Predictive Mean Vote (PMV) value ±0.5 over the office hours 6:00-18:00. The mean radiant temperature of the room was found below the room air temperature which resulted from the low RCC surface temperature of around 19°C. No condensation occurred on the panel during the system operation. The study showed that the RCC with DOAS comprising of cooling coil (CC), round around coil (RC) and enthalpy wheel (EW) is the most energy saving configuration.

1. Introduction

Thailand is situated in a tropical zone where the climate is hot and humid all year-round. Diurnal ambient air temperature ranges 25°C-35°C with relative humidity 50%-70%. Natural environment cannot provide enough thermal comfort, thus artificial environment must be built by energy-intensive air conditioners. Air conditioners contribute to 70% of the total energy consumed in the building [1]. This fact corroborates the study of energy saving potential of the mechanical way to maintain the thermal environment. The conventional air-conditioning is energy intensive as stated. Thus, it is desirable to develop alternative air-conditioning approaches to thermal comfort at low energy expense.

An alternative solution to conventional air conditioning is radiant cooling system. It consumes less energy and it has been successfully implemented in moderate climatic conditions, but it is quite challenging in real tropical region like Thailand as its cooling performance is limited due to high moisture content in the air. Using radiant cooling system with natural ventilation under the tropical condition the supplied chilled water temperature to radiant cooling panel is limited to 24°C[2] due to condensation at the surface of the radiant panel. The solution to this problem of condensation is the use of Dedicated Outdoor Air System (DOAS) coupled with radiant chilled ceiling (RCC). Using this system, radiant panel is offloaded from the dehumidification task, alleviating the condensation problem. It allows the radiant system to handle sensible load and can provide better indoor air quality as well[3]. RCC has application in modern buildings, due to high thermal comfort, energy-saving potential, and advantage of integration with building design and retrofitting in old building[4].
The performance of RCC with DOAS will give an insight of its operation on the tropical climate and illustrate how it differs from the countries with milder climate. The objective of this paper is to assess the energy saving potential of different configuration of RCC with DOAS in an office building in Thailand and compare them with the help of mathematical simulation using TRNSYS.

2. Methodology

2.1. RCC with DOAS

To harness the advantage of the energy saving, better thermal comfort and better vertical variation potential of RCC and to eliminate the prevailing disadvantage of its inability to handle latent load DOAS must be used. Thus, the system under investigation have two parallel units: Radiant unit (terminal unit) to take majority of the sensible load and the DOAS unit (auxiliary unit) to take the latent load and some part of the sensible load. Regarding the DOAS, various devices are combined to tackle the cooling load. Features of heat recovery like sensible wheel, enthalpy wheel, round around coil etc. are included with humidifier, dehumidifier and cooling coil for the performance enhancement of DOAS. DOAS when combined with different possible combination of the above-mentioned components have different energy performance under different climatic condition. In this study, three configurations of RCC and DOAS system were evaluated for their performance under the hot and humid climate of Thailand. The weather record from a meteorological station located at seven-story building of the school of bio resources and technology, in Bang Khun Tien Campus, King Mongkut’s University of technology, Thonburi (latitude 14.5° N and 100.5° E) was used as input for the weather condition in TRNSYS.

(a) RCC with DOAS (only Cooling Coil (CC))

(b) RCC with DOAS (with cooling coil (CC) and round around coil (RC))

(c) RCC with DOAS (with cooling coil (CC) and round around coil (RC) and enthalpy wheel (EW))

Figure 1. The selected configurations of RCC and DOAS system
Figure 1(a) shows the diagram of the configuration 1, RCC with Cooling coil (CC) as DOAS, which reduces the temperature and humidity of the outside air (OA) and supply it to the radiant room (supply air: SA). The air inside the room will be exhausted (exhaust air, EA) in the same amount as OA supplied to the room. The return air (RA) is mixed in the air mixing valve with the OA. ‘Figure 1(b)’ is the diagram of configuration 2, which have an additional run-around coil (RC) than configuration 1, for dedicating the cooling coil to handle the latent heat by precooling the SA on the primary side of the RC before going to CC. The air then passes through the secondary side where it gets reheated after passing through the CC. Configuration 3, shown in ‘Figure 1(c)’, where enthalpy wheel (EW) is added to the components of configuration 2, which aids heat recovery from EA. The chilled water at 7℃ is supplied to DOAS and 15℃ (for configuration 1 and 3), 15.2 ℃ (for configuration 2) is supplied to RCC by two different chillers as shown in ‘Figure 1’. Chilled water at 15.2 ℃ and 15 ℃ are respectively supplied to configuration 2 and configuration 1 and 3 to ensure the comfort requirement is met without and condensation on the panel.

2.2. RCC with DOAS

The building model in this study is a one storied square shaped office building prototype, width 20m × 20 m, height 3 m (area 400m²). The building facades faces four cardinal directions (N, E, S and W) with fenestration on all the façade. Figure 2 shows the 3-d model of the building to be conditioned.

Figure 2. Building Model

The building is squared in shape (20×20×3 m) with fenestration on each facade. The opaque part of the wall consists of polyurethane insulation layer (0.02 m), plaster (0.01 m) brick (0.1 m) and plaster (0.01 m) with a total thickness of 0.14 m and the total heat transfer coefficient (U) is 1.008 W/m².K. The windows on the four walls of the building consist of clear glass of thickness 6 mm. The window to wall ratio is 0.4. The U value of the glass is 5.73 W/m².K and shading coefficient (SC) is 0.5. The roof is made up of 0.15 m concrete cement layer and 0.05 m polyurethane layer with U value of 0.519 W/m².K. The roof area is 400 m² on which there is RCC of 320 m² where the U value is 0.487 W/m².K. Chilled water is supplied to the RCC at the rate of 14,000 kg/hr. through a chiller at 15/15.2 ℃. The pipes for chilled water flow on the panel have 0.145 m spacing, the inside diameter of the pipe is 0.0012 m. The floor is made up of 0.15 m concrete cement layer with U value of 3.448 W/m².K.

2.3. Building usage

It was assumed that the office was operated from 6:00-18:00. The power density of the lighting and the equipment was set as at 6 W/m² and 10 W/m², respectively. The building occupancy was assumed as 1 person for 10 m² floor area. The variation of occupancy, lighting and equipment power with time is shown in ‘Figure 3’. The office is assumed to have a high air tightness with air infiltration of 0.3 ACH (210 cfm/floor) and ventilation rate calculated according to AHSRAE standard is 11.5 cfm/person. There are two period of operation of the system. The precooling period from 2:00-6:00 where the air is cooled with recirculated air from the room by the DOAS at 1300kJ/hr. The operational period where 1000kJ/hr of the fresh OA is mixed with the 300kJ/hr of RA in mixing valve, RCC is also operated in this time period. Air in both the period are passed through air mixing valve but during operational period the air is mixed at the valve while during the precooling period the OA is not supplied to the air mixing valve.
2.4. Comfort parameters
The evaluation of human comfort in TRNSYS is based on the Fanger’s PMV model, with the clothing insulation of 0.5 clo, activity level of 1.2 met, wind speed 0.05 m/s. These parameters are inserted in the TRNSYS for simulation.

2.5. TRNSYS Simulation
TRNSYS 17[5] software was employed to simulate the operation of the radiant system with different DOAS configuration.

![Characteristics of building usage](image)

Figure 3. Characteristics of building usage

The simulation was run in a manner that it provided thermal comfort condition during the working hours by connecting different modules (which are mathematical codes) to make a complete system. Three configurations comprising RCC with DOAS were built in modules of respective configurations and were connected to building type 56 module in TRNSYS simulation studio. Type 56 module is facilitated with TRNBuild sub-program for assigning the different parameters for the building. RCC is contained in the type 56 module of TRNBuild sub-program. Type 9e facilitate the user to feed the user defined water temperature values of the chilled water to RCC created through a file. Type 9e also serves the purpose of reading the weather data from a data file created by the user via the detail weather data from the workstation. Type 752 is a module for cooling coil which uses bypass fraction approach for CC to solve for the outlet air temperature. The air flow rate into the CC is 1000 kg/hr. Type 689 is a module for RC that is responsible for transferring sensible heat from inlet air stream to secondary air stream. Type 667 is a module for EW where two air streams are passed near each other so that both energy and moisture will be transferred. Type 14 h is a module for a time dependent forcing function which has a behaviour characterised by a repeated pattern, used for scheduling the operation hours for the CC and the overall system. Type 33c is a module for Psychometrics (dry bulb temperature and humidity ratio known). When the dry bulb temperature and humidity ratio of a state is known it calls the TRNSYS psychrometric routine, returning dewpoint temperature, wet bulb temperature, relative humidity, absolute humidity and enthalpy. Type 99 is the radiation processor and weather data reader as well which takes input data, total radiation and horizontal radiation of one-hour interval on a horizontal surface. This component then interpolates the radiation data, calculates several quantities related to the position of the sun and estimates solar radiation on several surfaces of either fixed or variable orientation. Type 65 c is the graphic online plotter with output file graphics component, used for displaying selected system variables. It prints the given data, once per time step to a user defined external file. Unit descriptors (kJ/hr, kg/s, ℃, etc.) are not printed to the output file. The indoor condition, chilled water and air condition and cooling load are generated and calculated from TRNSYS.

2.6. Power consumption by the chiller
A general reciprocating air-cooled chiller model[6][7] was used to calculate the instantaneous power consumption (kW). This model requires rated capacity, rated full-load power, cooling load, outside air dry-bulb temperature and chilled water supply temperature to calculate the instantaneous power consumption of the chiller.
3. Results and Discussion

3.1. Simulation for a hot and humid day

‘Figure 4 (a)’ shows sample data of June 5 taken as a base/reference case to represent the hot and humid day. The total solar radiation and the diffuse solar radiation are relatively low and close showing a cloudy day and the air temperature is between 28-35°C, relative humidity 60-90 %. The radiation in each building façade is shown in ‘Figure 4(b)’ which is calculated by TRNSYS module type 16i. From ‘Figure 4(b)’ total solar radiation had the highest value of 689.5 W/m² at 16:00 hrs. The incident solar radiation on the west wall has highest value of 518.9 W/m² and the highest temperature was 33.92°C.

![Figure 4](image-url)

(a) The solar radiation and the ambient condition  (b) Total radiation on each building façade

3.1.1 Configuration 1. The simulation results show the different condition of the air and chilled water used to cool the room and the indoor condition of the room as well. According to the ‘Figure5(b)’, the chilled water supply temperature (Tchs) is 15°C, which picks up the heat from the room and the resulting return chilled return water temperature (Tchr) is in the range of 16-16.9°C, with an increment of (1-1.9°C). Surface temperature of the RCC (Tpanel) is between 18-18.6°C during the air conditioning period of 6:00 to 18:00. For the DOAS. ‘Figure 5(a)’, the condition of the outside air is, temperature(Tamb) 25-33.92°C, humidity ratio (Wamb) 0.018-0.02 kgw/kgda which is mixed with the RA during the office hours and introduced directly during the precooling period results in air temperature (Tmix) and humidity ratio (Wmix) in the range of 24-32°C and 0.0093-0.0178 kgwv/kgda.

The air is further reduced by the cooling coil (CC) to supply temperature (Tsup,ven) 9°C and humidity ratio(Wsup,ven) 0.007 kgw/kgda. The air coming from the CC is mixed with the return air (RA) brings the room temperature at the range of 23-25°C with relative humidity 57.5-68.9%(humidity ratio around 0.0125 kgw/kgda). The dew point temperature (Tdp) in the room lies in between 13.4-17.6°C which is below the RCC panel temperature ensuring no occurrence of condensation as in ‘figure 6’. Initial drop in Tdp in the room can be seen in the graph due to precooling period of the room where there is no internal cooling load. It can be seen from ‘Figure 6’ that the mean radiant temperature (Tmrt) and operative temperature (Top) is almost equal to the room air temperature (Trm) during the office operational hour which means the cooling in the room is dominated by RCC. During the initial precooling period, Tmrt and Top are higher than Trm illustrating the dominant form of cooling is DOAS. Tmrt is higher than Trm from 6:00 a.m. to 9:35 a.m., the time taken by the radiant system to cool the walls.
It can be seen from ‘Figure 7’ that the thermal sensation of the room represented by PMV is within comfort range of ± 0.5 as prescribed by ASHRAE 55 [8].

3.1.2. Configuration 2. ‘Figure 8’ to ‘Figure 10’ show the condition of the room air-conditioned by configuration 2. During the precooling period from 2:00-6:00 the air is recirculated from the room while during the operational period the hot and humid ambient air (Tamb ≈ 25-35 °C, Wamb ≈ 0.019 kgw/kgda) is mixed with the RA (Tmix ≈ 25-32.4 °C, Wmix ≈ 0.009-0.0173 kgw/kgda) coil where the air is pre-cooled at (Tpre ≈ 17.5-22.5 °C, Wpre ≈ 0.017 kgw/kgda) (‘Figure 8(a)’). The air temperature and humidity ratio after passing through the cooling coil is same as that of configuration 1 but the supply air temperature to the room is raised by reheating of the air on the secondary side of the run-around coil (Tre≈17-20.5 °C). The Trm and Wrm are in the range of 23.9-27 °C and it can be seen from ‘Figure 8(a)’ and ‘Figure 9’. Tdp is in the range of 13.9-17.6°C and Tpanel is in the range of 18.5-19.4, ensuring no condensation. The dew point temperature of the room was brought down from 23.3 °C to 13.9°C to avoid condensation in the RCC panel. The SA to the room for configuration 2 is higher than configuration 1, enabling the RCC to absorb more heat. The mean radiant temperature and the operative temperature are lower than the air temperature in configuration 2, as seen in ‘Figure 6’. The difference between the Tmrt, Top and Trm in configuration 2 is more than that in the configuration 1.
The PMV for configuration 2 lies nearly at ±0.5 (‘Figure 10’) but the PMV is higher than that of configuration 1. The panel temperature of RCC must be reduced to maintain the PMV of configuration 2 as same as configuration 1.

3.1.3. Configuration 3. ‘Figure 11’ shows the condition of the air and water at various states of the configuration 3. From 2:00-6:00 the air is recirculated from the room to mixing valve while during the operational period the hot and humid ambient air (Tamb ≈25-35 °C, Wamb ≈ 0.019 kgw/kgda) is mixed with the RA (Tmix ≈ 23.7-32.4°C, Wmix ≈0.0163-0.0173) in the air mixing valve. The air from the mixing valve passes through the enthalpy wheel (Tew ≈ 23.93-29.3, Wew ≈ 0.01-0.017 kgwv/kgda) where it exchanges heat and moisture with the exhaust air and then passes via the primary side of the RC to the CC and then the secondary side of the RC and then eventually supplied to the room. The temperature of the mixed air is dropped with reduction in humidity (0.005kgw/kgda) after the air passes through EW. The air then flows through the primary side of the run-around coil with precooling temperature (Tpre) close to that of the configuration 2 with lowers humidity. The installation of the EW therefore has a huge contribution to reduction of humidity, but this will lead to reduction in the capacity of the run-around coil. The reheat temperature of configuration 3 is (16.4-19.1°C), lower than that of the configuration 2. Tpanel is in the range of (18.2-19.6°C) (as in ‘Figure 12’) while the dew point temperature in the room is in the range of (13.9-17.6°C) which means there is no condensation in the room. The dew point temperature of the air inside the room was brought down from 23.3°C to 13.9 °C during the precooling period. The mean radiant temperature is higher than the air temperature during
the initial operation of the RCC panel from 6:00 to 8:10 and after this period the air temperature is higher than the mean radiant temperature and the operative temperature illustrating the room is cooled by the mode of radiation (as in ‘Figure 13’). The PMV in configuration lies near to ± 0.5 (as in ‘Figure 14’).

3.2. Daily cooling Load Comparison
For configuration 1, the total cooling load is between 8.7-48 kWe during working hours (8:00-17:00) (‘Figure 15(a)’). Most of the load is taken by the RCC (21-20.2 kWe) which accounts for 62% of the total load. The DOAS has cooling load of 8.7-18.2 kWe with latent heat slightly higher than sensible heat. Due to the air infiltration of 0.3 ACH/400 cfm, the DOAS system must be started at 2 am to bring down the dew point temperature in the room to safeguard against condensation. ‘Figure 15 (b)’ is the cooling load for configuration 2 (6-45.8 kWe) which is lower than configuration 1 (as 15.2°C, lower chilled water also enables some saving). However, in the case of configuration 2, more sensible heat is handled by the RCC (22.9-32 kWe) due to the reheating of the air on the secondary side of the round around coil after exiting the cooling coil. ‘Figure 15 (c)’ shows the reduction of load in configuration 3 as compared to the first two configuration. The cooling load of the system is in the range of 6.42.7 kWe. The load handled by RCC is in the range of (21.8-32.2 kWe) while the total cooling of DOAS is in the range of (6-11 kWe). Lower cooling load with this configuration is due to the heat recovery feature of the enthalpy wheel which contributes to lower CC load and the capability of the round around coil also dedicates the cooling coil to latent heat handling. The higher temperature entering the radiant room with low humidity ensures more sensible load handling by the radiant chilled ceiling. The sensible load handling capacity of the radiant chilled ceiling in configuration 3 is increased as the EW preconditioned the air and then it passes via the RC which dedicates the cooling coil to handle more latent load.
3.3. Monthly Cooling energy for the RCC and DOAS

‘Figure 16 (a), (b) and (c)’ shows the monthly cooling load of three configurations of RCC and DOAS. The maximum cooling energy consumption is for the month of May with cooling energy of 17479.34 kWth for configuration 1, 16187.08 kWth for configuration 2 and 15018 kWth for configuration 3. The minimum cooling energy consumption is for the month of February with cooling energy of 14175 kWth for configuration 1, 13026 kWth for configuration 2, 12339.21 kWth for configuration 3.
Figure 16. Monthly cooling load comparison of 3 configurations of RCC with DOAS.
3.4. Annual simulation for the RCC and DOAS

The annual cooling load of the three configuration of RCC with DOAS have been compared in this section. ‘Figure 17’ shows the simulation results for the whole year period. It can be observed that configuration 2 has 7.6% and configuration 3 has 13.4% less energy consumption than configuration 1. The lower energy consumption for configuration 2 is due to the ability of round around coil to dedicate the cooling coil to handle more latent load by precooling the air and the higher SA temperature due to heating of the supply air after the cooling coil ensures more sensible load handling from the RCC. The lowering of energy consumption in configuration 3 is due to the heat recovery feature of enthalpy wheel in conjunction with higher SA with less humidity. The share of cooling load handled by RCC panel is 58.8%, 67.1% and 71.5% in configuration 1, 2 and 3, respectively. The high load handling in configuration 2 and 3 is due to the higher air supply temperature provided by DOAS as compared to configuration 1.

Figure 17 Annual cooling load comparison

3.5. Electricity Consumption analysis by the chiller

With the help of the cooling load generated by TRNSYS and the reciprocating air-cooled chiller model[6] the electrical energy consumed by the chiller producing chilled water at 15/15.2°C for RCC and the chiller producing chilled water at 7°C for DOAS were calculated. The energy consumed by the chiller for RCC is about 58%, 64% and 68% out of total energy consumed for running configuration 1, 2 and 3, respectively. Less energy is devoted to chiller for configuration 2 as the chiller water temperature is 15.2°C. Configuration 2 and 3 save 8% and 13% electricity as compared to configuration 1. Configuration 3 saves energy by running the chiller dedicated to produce 15°C as major load. ‘Table 1’ shows the energy consumed by the two chillers that supply chilled water to the RCC and DOAS.

| Type              | Configuration | 1   | 2   | 3   |
|-------------------|---------------|-----|-----|-----|
| RCC Chiller energy (kW\text{elec}) | 29903 | 31483 | 31487 |
| DOAS chiller energy (kW\text{elec}) | 23240 | 17480 | 14633 |
| System energy (kW\text{elec}) | 53143 | 48963 | 46120 |

From the annual cooling load and annual energy consumption of the chiller, the Coefficient of performance (COP) of the respective chiller for different configuration is also calculated. The COP of the chiller for RCC and DOAS is 3.78 and 3.41 with difference of 0.34 for configuration 1, that for
configuration 2 is 3.79 and 3.33 with difference of 0.08 and COP of the chiller of RCC and DOAS for configuration 3 is 3.77 and 3.23 with difference of 0.54 respectively.

4. Conclusion
This paper reported the comparative study of RCC equipped 3 DOAS configuration in hot and humid climate. The dew point temperature is always lower than the RCC panel temperature for all the investigated configuration, ensuring no condensation. While the mean radiant temperature and the operative temperature are lower than the air temperature for all cases meaning cooling is dominated by the RCC. This shows that the RCC equipped with DOAS can be used in Thailand climate without any condensation. The annual simulation shows that configuration 2 has 7.6% and configuration 3 has 13.4% less annual cooling load than configuration 1. The RCC chiller for configuration 1, 2 and 3 consume 58%, 64% and 78% of the total energy consumed by the chillers for running the system. The Coefficient of performance (COP) of the chiller for RCC is higher than that of chiller for DOAS. Configuration 3 is the most energy efficient configuration for hot and humid climate of Thailand.

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