ANALYSIS OF RADIANT COOLING SYSTEM INTEGRATED WITH COOLING TOWER FOR COMPOSITE CLIMATIC CONDITIONS

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Abstract[*]

Increased demand for cooling leads to consumption of a significant amount of energy by heating, ventilation, and air-conditioning systems in buildings. The building envelope acts as a thermal barrier and plays a significant role in improving building energy efficiency. Radiant cooling systems, which often use the building structure for thermal storage and to provide thermal comfort, have the potential for saving peak power in buildings. In the current study, both experimental and a simulation study were performed for two operational strategies of radiant cooling systems: a cooling tower–based system and a more conventional chiller-based system. The cooling tower–based radiant cooling system is compared with the chiller-based radiant cooling system for achieving annual energy savings. Experiments were conducted for the chiller and cooling tower–operated radiant cooling systems. Based on experimental data, whole building simulation models of both the cooling tower– and the chiller-based systems were calibrated. Simulations for both systems were carried out for 1 year. The annual simulation results show that the cooling tower–operated radiant cooling system saves 14% energy compared to the chilled water–operated radiant cooling system.

Introduction

The energy crisis scenario has helped define "sustainable development" in many areas. In the building industry, it has come to mean energy saving without compromising thermal comfort. The energy consumed by buildings, which is a major component of total global energy consumption, currently is more than 30% of all energy consumption and is expected to increase in the future. Typically, an air-conditioning system contributes about 60% to 70% of total energy consumption of existing residential households in urban and suburban areas in hot and humid Southeast Asian Region (Vangtook and Chirarattananon 2007). Radiant cooling systems are more energy efficient, along with peak power saving potential, than all-air conventional air conditioning systems (Stetiu 1999). Radiant cooling systems can provide energy savings of 30% compared to all-air systems (Khan et al. 2015). Results for a building with a thermal-activated building system show 20% lower energy consumption and better thermal comfort compared to an all-air variable air volume system (Henze et al. 2008). Radiant cooling systems and convective systems have been compared in terms of thermal comfort and energy consumption by using simulations for office buildings in warm and humid climate, radiant systems can be very effective cooling terminal units, utilising fairly high temperature cooling media and thus increasing the efficiency (Oxizidis and Papadopoulos 2013). Energy simulations of radiant slab cooling show 10%–40% energy savings for different climatic conditions (Tian and Love 2009). In radiant cooling systems, chilled water either flows through pipes or chilled ceiling panels to curb the sensible load in buildings. In radiant cooling systems, 60% of space cooling is achieved by radiative heat transfer from surfaces to the space around the surfaces; convective and conductive heat transfer handles the rest of the cooling load (Feustel and Stetiu 1995). Energy savings and system performance of radiant cooling systems with desiccant cooling have also been analyzed. Results shows that chilled ceiling radiant cooling system with desiccant based systems can provide up to 44% savings in primary energy consumption (Niu, Zhang, and Zuo 2002). Radiant cooling systems do not have the ability to cater latent load; hence, condensation may occour on the chilled surface. To avoid condensation, add-on supplemental systems must be coupled with radiant cooling systems (Saber et al. 2014), e.g., additional systems with controls and dew point offsets to maintain indoor air quality (Conroy and Mumma 2001). In hot and humid climate, operation of radiant cooling systems has the additional challenge of condensation that needs to be taken care of. To avoid any condensation, the radiant surface temperature must be higher than the dew point temperature of zone air. Application of evaporative cooling (cooling tower) to supply cold water to radiant cooling systems for residential houses has shown that cooling towers could be used to provide cooling water for radiant cooling and for precooling of ventilation air to achieve thermal comfort (Vangtook and Chirarattananon 2007). Correlations were developed (Facão and Oliveira 2000) for heat and mass transfer coefficients for a closed wet cooling tower used with the chilled ceiling radiant cooling system to predict the thermal performance of the system. Chiller-operated, thermal-activated building systems exhibit 30%–50%

(a)　　　　　　　　　　　　　　　　　　　**(b)**

Figure 1: (a) Radiant cooling system; (b) chilled water plant

Higher energy demands for chilled water generation and distribution compared to systems with cooling towers (Lehmann et al. 2011). In this paper we used both simulation and experimental data to analyze the operation and impact of using cooling tower for providing supply water for radiant cooling systems. An energy model of a building with a radiant cooling system was developed and calibrated using the measured data. The calibrated model was used to estimate the performance and energy savings of cooling tower–assisted radiant cooling systems.

Experimental setup

A typical daytime-use office building at the Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur, India, located in the composite climate of India, was used in this study for experimentation as well as simulation. The building is two storeys, with floor to ceiling height of 3.5 m and total floor area of 1,500 m^2.The radiant cooling system is installed on the second floor of the building. The installed radiant cooling system is shown in Figure 1(a), and the installed plant is shown in Figure 1(b). This system is a chilled panel–based radiant cooling system coupled with a chiller and a cooling tower to feed the radiant cooling system. The system also contains a dedicated outdoor air system (DOAS) for incorporating fresh air and recovering the latent load.

Measuring instruments and sensors

Table 1 is a list of instruments and sensors used in the experiment. Resistance temperature detectors (RTDs) were placed in the test zone at different positions [four near the walls, five at the center at different heights (0.1 m, 0.6 m, 1.1 m, 1.7 m, and 2.4 m), and four for the panel temperature]. In-line RTDs were placed to measure the temperature of supply and return chilled water coming from the chiller and cooling tower. All the RTDs were calibrated before the tests. Temperature and relative humidity (T&RH) sensors were placed in the DOAS (six at the supply and return of each component). In-line ultrasonic flow meters were placed in the chilled water supply line. A Testo 480 kit [shown in Figure 2(a)], which contains an air velocity sensor and globe sensor for mean radiant temperature (MRT), was placed in the zone (center of the room at 1 m high). Figure 2(b) shows the Keysight data logger for logging the values

from the RTDs. Figure 2(c) shows the Horner data logger. Energy meters were used to get energy consumption for each component as shown in Figure 3(a), British thermal unit (Btu) meters were shown in Figure 3(b) in the experimental building. All T&RH sensors, energy meters, and British thermal unit (Btu) meters were connected in-loop with the data logger using the RS 485 communication protocol.

Table 1: Instruments and sensors

S.No.	Sensor/instrument	Accuracy
1	Temperature RTD (°C)	±0.2°C
2	Water flow meter (m^3/s)	±1%
3	Energy meter (kW, kWh)	±1%
4	T&RH sensor (°C and %)	±0.5°C and ±3%
5	Air velocity sensor (m/s)	±2%
6	MRT Globe (°C)	±0.5°C

Figure 2: (a)Testo 480 kit, (b) Keysight data logger, and (c) Horner data logger

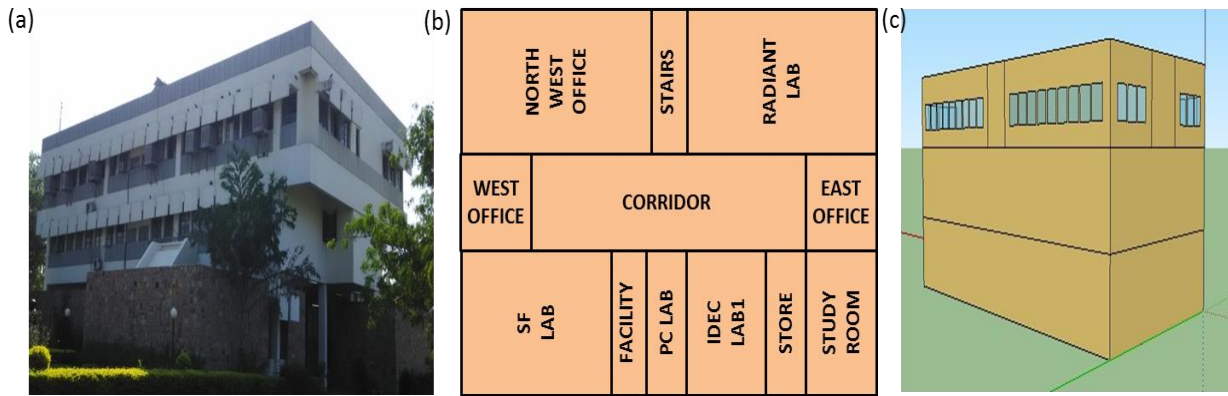*Figure 3: (a) Energy meter; (b) Btu meter display*

Figure 4: (a) Actual view of modeled building, (b) floor plan, and (c) isometric view of building model

Methodology

A typical daytime-use office building at an Indian university was used for experimental and simulation analysis of the radiant cooling system, a radiant cooling system integrated with a chiller and cooling tower, with a parallel DOAS. The actual building, second-floor floor plan, and an isometric model of the building are shown in Figure 4. The radiant cooling system has been integrated in the "Radiant Lab," as shown in the floor plan [Figure 4(b)].

Experiments were conducted for two radiant cooling system configurations.

Case 1:

A conventional radiant system was used for the base case: a radiant cooling system coupled with a chiller to feed chilled water to the system. In this case, chilled water was produced in a radiant chiller and supplied to the radiant panels to cater to the sensible load, whereas DOAS was used to cater to the latent load in the zone. A conventional chiller was used to feed chilled water to a cooling coil for dehumidification of air in the DOAS. In the DOAS, supply air first enters the energy recovery wheel, where it exchanges heat with return air and then enters the cooling coil. Figure 5 is a schematic diagram of the base case.
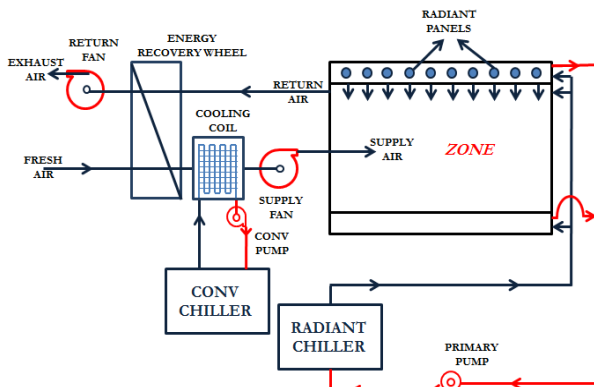

Figure 5: Radiant cooling system operated with chiller

Case 2:

In this case, the chilled water in the radiant cooling system is supplied from a cooling tower instead of the chiller to cater to the sensible load, and chilled water in the cooling coil of the DOAS is supplied from a chiller to cater to the latent load. Demineralised water is used in the radiant loop, and normal tap water is used in the cooling water loop. To protect the radiant cooling system from scaling, dirt, and impurities a plate heat exchanger is used in between. Figure 6 is a schematic diagram of the radiant cooling system operated with a cooling tower.

This work is conducted in three phases.

- Experiments were conducted on the second floor of the building in a 67.8 m^2 (730 ft^2) room, shown in Figure 1(a).
- Different parameters such as indoor thermal performance and thermal energy were evaluated from the logged data. A whole building energy model was prepared in EnergyPlus version 8.6 developed by United States department of energy (USDOE) and calibrated by comparing the experimental data for thermal energy with the simulation predicted thermal energy.
- Based on the calibrated model, annual simulation results were analyzed for the base case, and cooling tower–integrated radiant cooling systems.
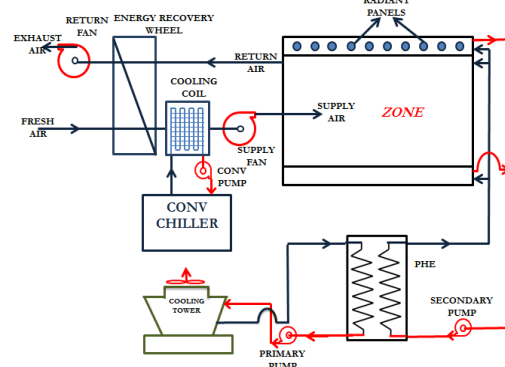

Figure 6: Radiant cooling system operated with cooling tower

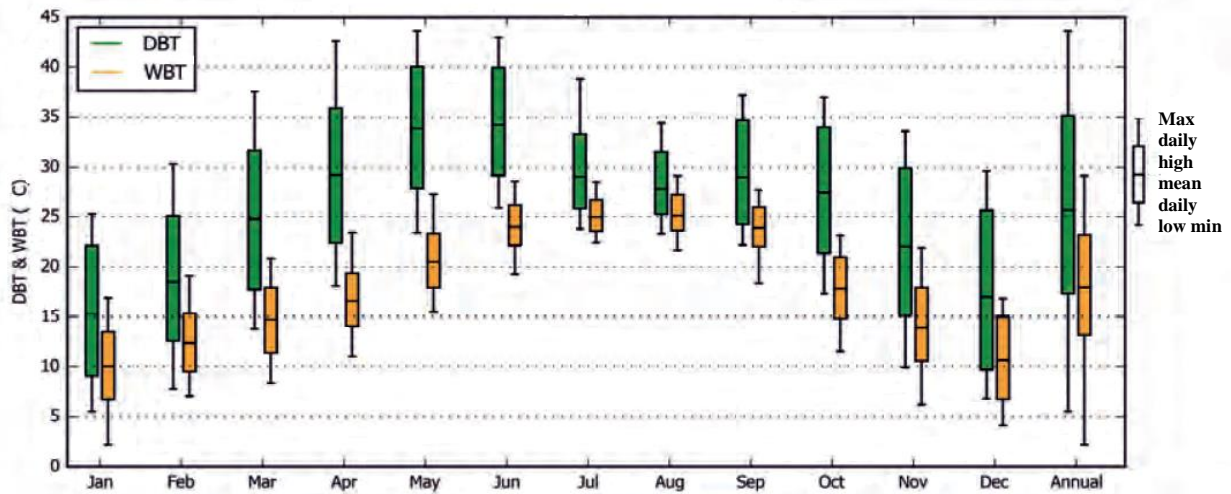## Weather conditions at Jaipur (composite climate)

Figure 7: Monthly statistics of dry bulb temperature (DBT) and wet bulb temperature (WBT)

Figure 7 shows the monthly statistics of dry bulb temperature (DBT) and wet bulb temperature (WBT) for Jaipur (ISHRAE weather file 2017). The cooling tower water outlet temperature has been analyzed, and the temperature of the water was found to be less than 24°C for 64% of the total daytime period and 70% of the total nighttime period. (Note: Chilled water above 24°C cannot be used for supply in radiant cooling systems.) The availability of water by cooling tower during the night period to achieve much lower temperature was high i.e. for the 57% of total night time period the water available at a temperature lower than 20 °C whereas it was 44% during the day time period. The temperature distribution of cooling water available from the cooling tower for Jaipur is shown in Figure 8.
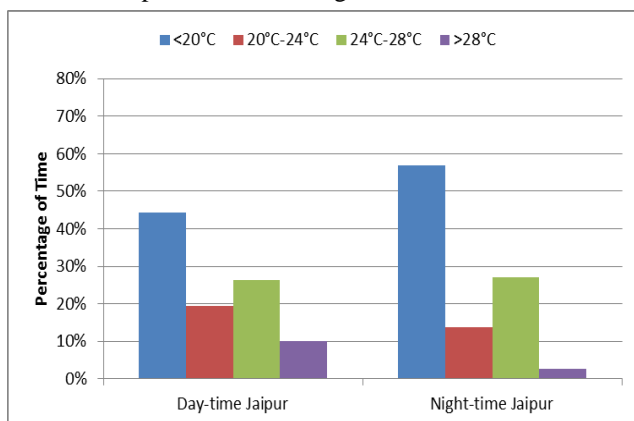

Figure 8: Annual availability potential of cooling water from cooling tower for Jaipur

Model simulation and calibration

Both cases were simulated for the composite climate of Jaipur using EnergyPlus. The weather file used for the EnergyPlus simulation was created by using the site weather data gathered by MNIT Jaipur weather station. Yearly run time was considered for the simulation. In simulations, a fixed-occupancy pattern of 10 persons was considered and office hours from 9:00 a.m. to 5:00

p.m.; no occupancy was considered during weekends. Sensible load for ten persons was provided while conducting experiments, same was used in simulatuion of the model. Building construction and internal gains are provided in Table 2.

Table 2: Building construction and operational parameters

Building parameter	Unit	Value
U-value of structure	W/m²-K	Exterior wall—1.625 Roof—0.439, Windows—2.72
Solar heat gain coefficient of windows	Fraction	0.764
Visible transmittance of windows	Fraction	0.812
Window wall ratio	Fraction	0.20
Lighting power density	W/m²	5
Electric power density	W/person	60
Occupancy	Person	10

Figure 9 is a schematic of the radiant cooling setup. The heating, ventilation, and air-conditioning (HVAC) system comprises the chilled ceiling radiant cooling system in which chilled water can be fed either through the chiller or through the cooling tower. Two constant coefficient of performance (COP) chillers are used for the radiant cooling system and cooling coil of the DOAS. A cooling tower with an approach of 3°C is used in the model. In Case 2 (the cooling tower–coupled radiant cooling system model), when the total cooling load is not met, the DOAS runs in recirculation mode to meet the remaining cooling load. For modeling the radiant cooling systems in EnergyPlus, the supply side and demand side were prepared for the chiller-based system, and then in the supply side chiller was replaced by the cooling tower to provide cold water to the panels. Layer by layer construction was used for the radiant

surface modeling in the object "construction internal source". The DOAS was modeled by creating an air loop that consisted of the cooling coil and the energy recovery wheel.

Table 3 shows the HVAC system configuration parameters. Because measured data for the experimental building are available, a calibrated model was developed to achieve more accurate simulation results. The US Department of Energy has given calibration criteria based on the normal mean bias error (NMBE) and the cumulative root mean square error (CvRMSE) for cooling energy, the calibration of the model was done based on the paremeters (Nexant 2008).

Table 3: HVAC system configuration parameters

Parameter	Value
HVAC system type	Radiant chilled ceiling system with DOAS
Fan design	Constant volume with 0.339 m³/s (200 CFM)
Supply air temp. set point	16°C–19°C

Parameter	Value
Chiller parameter	DOAS chiller autosized with 3 COP and 12°C leaving chilled water temp. Radiant chiller autosized with 3.5 COP and 16°C supply chilled water temp.
Cooling tower	Approach 3°C
Radiant pipes diameter and spacing	15 mm and 150 mm
Ventilation	20 CFM/person
Zone set point temp.	27°C

The experiments were performed in the single zone of the second floor of the building; the chiller-operated radiant cooling system was considered as the reference or base case model and was calibrated using the experimental values. Figure 10 shows the calibration of the model in terms of thermal energy with the measured data. The NMBE and CvRMSE are −8.40% and 20.09% respectively, which are lower than the hourly limits for an hourly calibrated model.
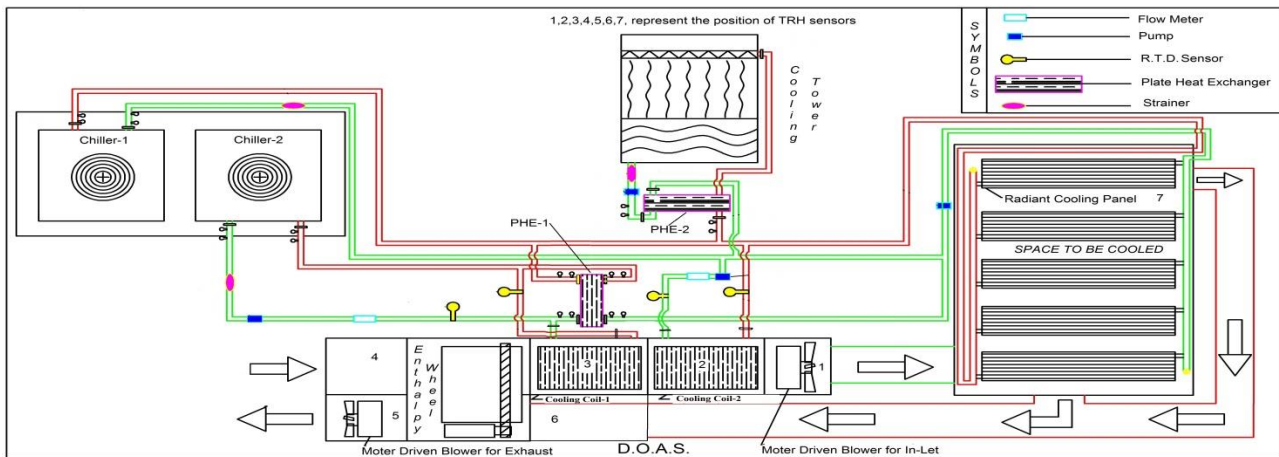

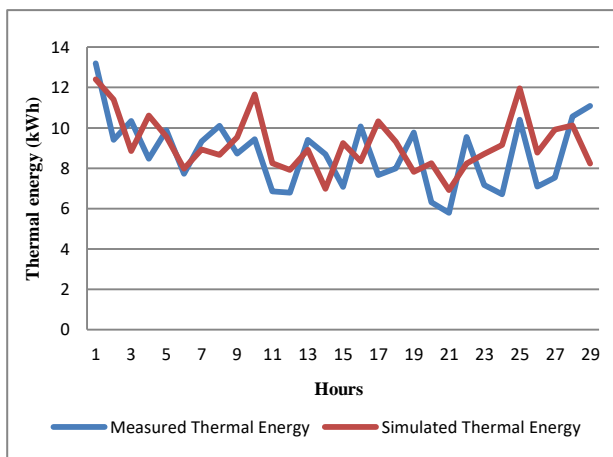*Figure 9: Schematic of radiant cooling system*

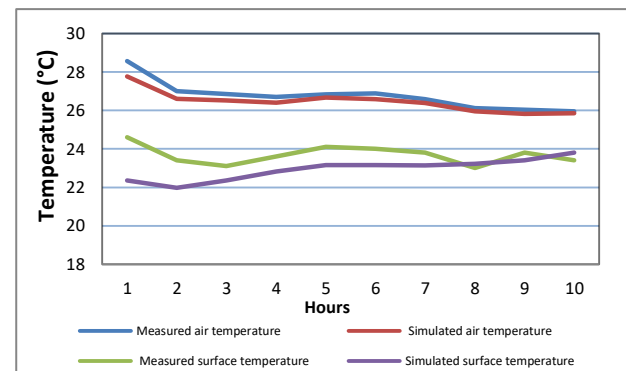*Figure 10: Calibration of model using measured and simulated data*

Figure 11: Comparison of measured and simulated radiant surface temperature, measured surface temperature, and simulated surface temperature

Results and discussion

Figure 11 shows the comparison of measured and simulated air temperature and measured and simulated radiant surface temperature for the zone. Annual energy consumption for different components of the radiant cooling system for both the cases is shown in Figure 12. By replacing the chiller with the cooling tower, chiller energy consumption was reduced by 47%, but the DAOS energy consumption increased, resulting in the increase of conventional chiller energy consumption by 21%. Pumping energy in Case 2 increased by 49% due to enhanced flow of the cooling tower. Overall, the cooling tower–operated radiant cooling system achieved a 14% annual energy saving compared to the chiller-operated radiant cooling system.

Figure 13 shows the monthly energy savings of the two radiant cooling systems. In the month of May, the maximum monthly energy savings of 198.1 kWh was achieved for the cooling tower system. The difference in energy consumption between the chiller- and cooling tower–based systems is maximum in May due to the lower WBT. Also, the performance of the cooling tower system is comparably better and the radiant cooling system can handle the sensible load most effectively in the month of May. In the month of April, monthly energy savings was 143.9 kWh, which is slightly lower than in May due to the reduced cooling load requirement in April. In the Months of January, February, November,

and December, energy savings were minimal as there is almost no requirement for cooling; the only requirement in winter is to provide fresh air. Also, in the months of February and October the cooling tower has a good potential to couple with the radiant cooling system to get energy savings. In the months of February and October, 79.2 kWh and 93.1 kWh, respectively, of energy savings were achieved. Figure 14 shows the variations in monthly energy savings with respect to DBT and WBT.
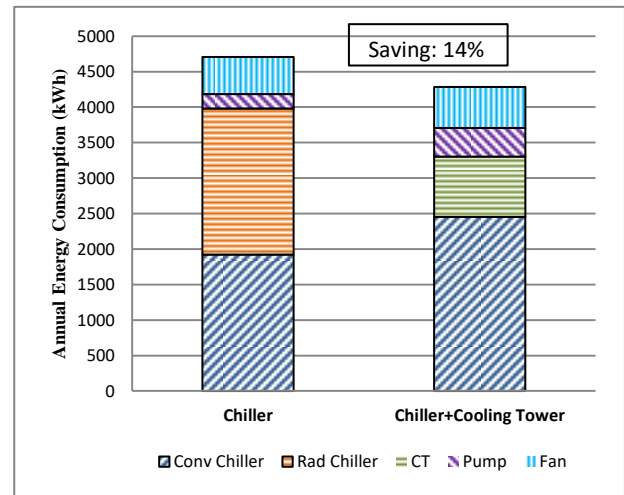

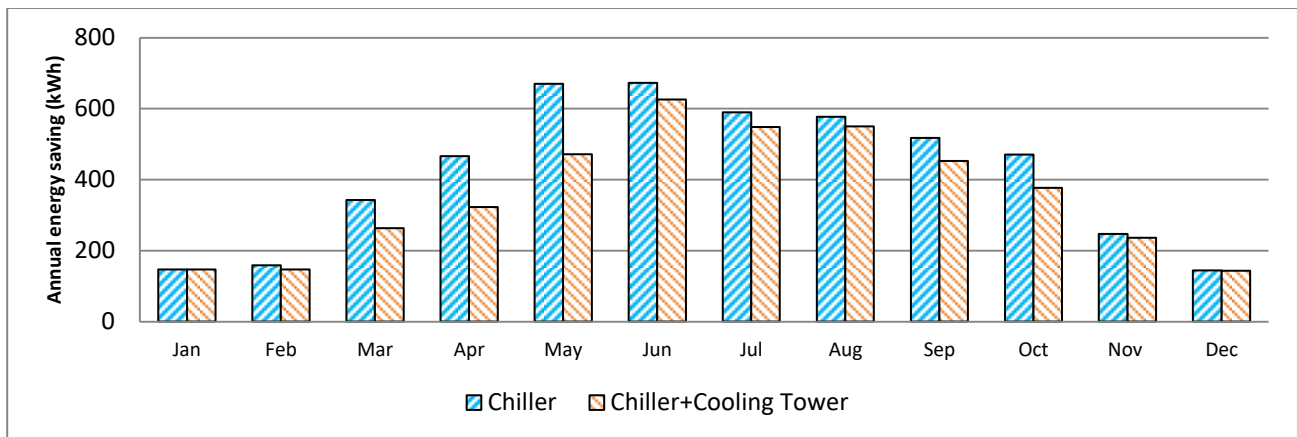*Figure 12: Annual energy consumption of chiller- and cooling tower–operated radiant cooling systems*

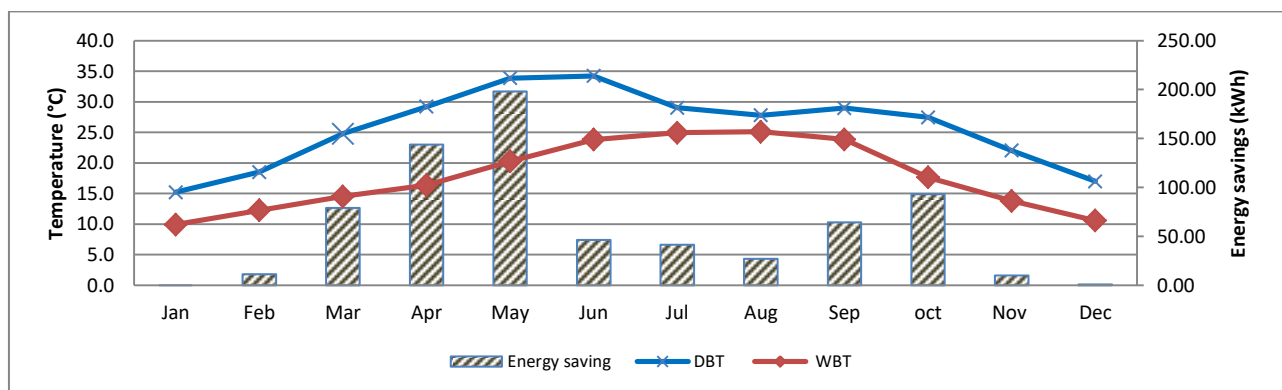*Figure 13: Energy savings of chiller- and cooling tower–operated radiant cooling systems*

Figure 14: Ambient dry bulb temperature (DBT), wet bulb temperature (WBT), and energy savings

Conclusion

The quasi steady state behavior of a radiant cooling system under different operating conditions in a composite climate was demonstrated using EnergyPlus. The performance of a chilled ceiling radiant cooling system operated with either a chiller or a cooling tower with a parallel DOAS was analyzed in terms of thermal energy and energy consumption for the composite climate. In the cooling tower–operated radiant cooling system, a total yearly savings of 14% was achieved compared to the chiller-operated radiant cooling system for the target building in composite climate. In the month of May, the month in which the maximum monthly energy savings was achieved, the energy savings for the cooling tower–operated radiant cooling system was 31%. These results indicate that a parallel cooling tower with the existing radiant cooling system could provide possible energy savings. If the WBT is lower, to achieve the desired chiller water temperature the cooling tower should be used.

Acknowledgment

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