Performance Evaluation of Personalized Radiant Conditioning System for Cooling Mode

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Abstract

The radiant systems consume less energy and provide better thermal comfort as compared to the Conventional system, but the main drawback of this technology is condensation and inability to cater the latent load. These challenges have directed many researchers to move their emphasis towards Personalized Conditioning System which aims to generate a microclimate zone near the vicinity of occupant according to need. This study is focused on Personalized Conditioning System when it is combined with a radiant system. The objectives of this study are 1) Evaluate the performance analysis of the system in cooling mode and, 2) Evaluate the performance of PRCS for cooling mode on different radiant cooling systems. An experimental setup of an office cubicle has been designed and fabricated using radiant panels at MNIT Jaipur, India. Three cases of the experiment were designed to evaluate and compare the performance of the system which are: Only Radiant Cooled Ceiling System (RCCS), Only Personalized Radiant Cooling System (PRCS), and both PRCS and RCCS coupled. It was observed that PRCS alone is sufficient to reach the thermal comfort criteria with low energy consumption, but it was unable to maintain the background temperature. When PRCS coupled with RCCS, it gives maximum thermal comfort for high supply water temperature ranging from 17 °C to 21 °C.

Introduction

In today's era of the energy crisis, providing comfort in buildings with energy efficient technologies has become a necessity. As per Statistics, 70 % of the building area falls under space cooling by Kumar (2011)**.** According to Bureau of Energy Efficiency (2006), about 32 % of energy use in a commercial building comes under space cooling, and this percentage rises to 45 % for residential buildings**.** Energy-efficient buildings are only effective when the occupants of the buildings are comfortable. In the most recent years, an improved lifestyle in some of the developing countries has showed an increase of energy demand, and it is expected that there will be raise in the utilization of energy resources in coming years.

The Radiant Cooling system is considered one of the most effective cooling solutions, which has been in use for a long while now. It can save around 40 % of energy over a conventional system.

Khan (2015) studied energy savings potential of a radiant cooling system installed in a commercial building in India. Energy simulations were carried out using FLUENT and EnergyPlus software to evaluate thermal performance and energy consumption. The study reports that radiant system was 17.5% more efficient than a conventional all-air system. The Computational Fluid Dynamics (CFD) simulation results showed that a radiant system offers more uniform temperatures, as well as a better mean air temperature range than a conventional system.

Although radiant cooling is superior to conventional cooling; it still has a major issue of condensation which can only be controlled by controlling the temperature. Also, thermal comfort requirement varies from person to person due to physiological, behavioral, & psychological adaptation. To fulfill the individual requirement, Personalized Conditioning System (PCS) is one way that brings cooling closer to the user, which allows adjusting the microclimatic environment. In this way, the energy is deployed where it is needed, and the individual needs for thermal comfort are fulfilled.

Watanabe (2007) developed two chairs incorporated with two fans, one under the seat and another one behind the backrest to provide isothermal forced air flow to the chair occupant. It was found that occupants feel neutral when room temperature was 28°C irrespective of fan speed.

Oi (2011) investigated the effects of heated seats and foot heaters in vehicles on thermal sensation and thermal comfort. The heated seat and foot heater improved the occupant's thermal sensation and comfort in cool environments. Also, operative temperature decreased by about 3°C.

Croitoru (2011) studied the office cooling systems based on all air mixing ventilation systems alone or coupled with radiant ceiling panels. This study was performed with simulating a typical two-desk office equipped with an all air mixing ventilation system. Then the numerical studies extended to the coupled mixing ventilation and cold radiant ceiling panels. The study shows that applying radiant ceiling panels reduce such kind of problems.

Sun (2012) designed a chair equipped with fans to enhance the convective plume. It has been tested in conjunction with displacement ventilation. This method provided additional cooling and improved the thermal comfort without the need to decrease the supply temperature of the displacement ventilation, which can lead to a risk of draft discomfort.

Veselý (2015) introduced a personalized heating system which consists of a neck-hand-foot heater. The system was evaluated on different human subjects under mild cool conditions at an operative temperature of 18°C. Results showed that the personalized heating could maintain thermal comfort beyond the commonly used heating set point, which gives a potential for energy savings due to higher effectiveness.

Khare (2015) studied a personalized cooling system using the principle of radiant cooling integrated with the conventional all-air system to achieve better thermal environment at the workspace. The analysis showed that personalized radiant system improves thermal environment near the workspace and allows all-air systems to work at higher thermostat temperature without compromising the thermal comfort, which in turn reduces its energy consumption.

This study combines Radiant conditioning technology and potential of PCS with the combination of a radiant system. The objectives of this study are 1) Evaluate the performance analysis of the system for cooling mode and, 2) Evaluate the performance of PRCS for cooling mode on different radiant cooling systems.

Design of Personalized Conditioning System

Personalized radiant conditioning system has been installed on a building at MNIT Jaipur. The experimental room has the size of 6 m x 3 m x 3.5 m (l*b*h). The room is north facing, and it has two south facing windows of size 1.3 m x 1.2 m (l*h). There is no provision for direct sunlight from the window because of overhangs. Figure 1 shows detail room layout with radiant ceiling and radiant cubicle.

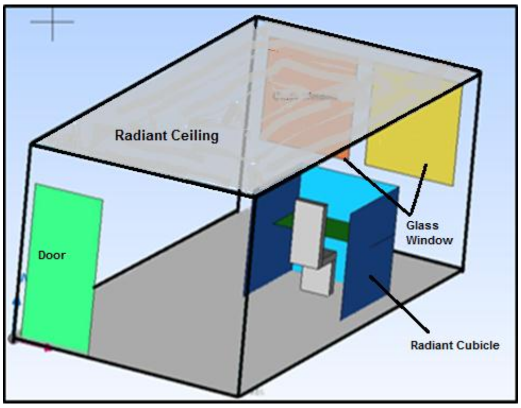

Figure 1: Room Layout

A standard size wooden (plywood) office cubical was built for the experiment. During construction of cubical, radiant panels (0.6 m x 0.6 m) were fitted into the plywood. An insulation of 9 mm thick sheet of nitrile rubber applied between panels and structure to minimize the heat losses. Total 12 panels (4 panels each side) were used for the construction of PRCS. Panel connection arrangement has done in series for the applicable flow of water in each panel with the help of PU pipes. These panels have 20 mm size oval shape roll bonded circuit for water circulation. Figure 2 shows the schematic of the cubicle.

Figure 2: Schematic of radiant cubicle setup

Measurement Parameters

For thermal comfort study, both environmental and psychological parameters were measured. Data loggers used to take measurements with keeping time interval of 10 minutes for the overall duration of the experiment after it reached a steady state.

- Water outlet and inlet temperature from chiller
- Flow rate of re-circulating water
- Indoor air parameters at different height and directions
- Mean Radiant Temperature (MRT)
- Ceiling panel surface temperature
- Energy Consumption

Operative Temperature (OT)

ASHRAE suggests that a simple averaging of MRT and DBT gives acceptable results of Operative temperature. The average of MRT and DBT weighted by their respective transfer coefficients, i.e. the following expression given by Winslow (1937):

$$\mathrm{OT} = \frac{h_r\, MRT + h_c\, DBT}{h_r + h_c}$$

Where h_r and h_c are radiation and convection coefficients and DBT is Dry Bulb Temperature also known as air temperature.

Standard Effective Temperature (SET)

As per ASHRAE Standard 55-2013, SET is defined as the temperature of an imaginary environment at 50% RH, < 0.1 m/s average air speed , and MRT is equal to DBT. The total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that of a person in the actual environment, with actual clothing and activity level.

Experimentation for Summer Cooling

For the cooling experiment and evaluation of thermal comfort, the only parameter considered was inlet water temperature. The range of chilled water temperature kept from 15°C to 21°C. The lower limit of the supply water temperature was decided by dew point temperature.

Three different cases were considered for the performance analysis of PRCS as - Only Radiant Cooled Ceiling System (RCCS); Only Personalized Radiant Cooling System (PRCS); Both PRCS and RCCS running.

The methodology of the experiment is shown in figure 3.

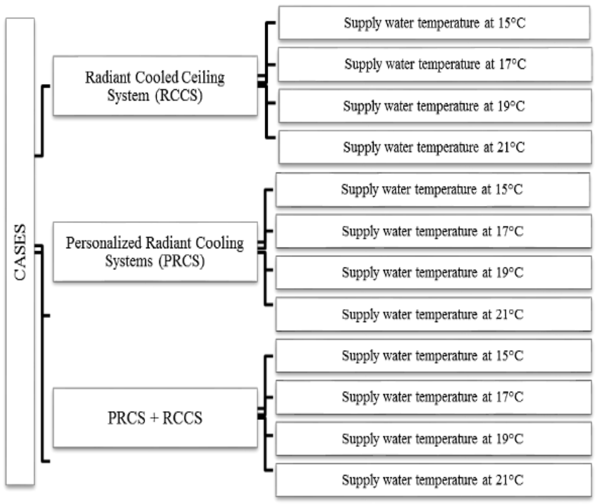

Figure 3: Different cases for cooling experiment

Repeated numbers of experiments were performed for each case from April 2016 to May 2016. For this duration, ambient temperature varied from 32°C to 38°C.

Results and Discussions

In order to evaluate the performance of PRCS on cooling mode, several experiments were conducted in the summer season with varying inlet water temperature only. There are three different cases has been selected (described previously) to compare the performance analysis of PRCS. The results for all cases are explained below:

Analysis of Measured Parameters

Radiant Cooled Ceiling System (RCCS):

For Case-1, only Radiant Cooled Ceiling System has been run on different supply water temperature. During the experiment, supply water temperature, MRT, Air Temperature were monitored and OT, SET were calculated. Table 1 and Figure 4 shows the performance of RCCS on different supply water temperatures.

Table 1: Variation in different indoor temperatures

Chilled water temp. (°C)	MRT (°C)	Air temp (°C)	OT (°C)	SET (°C)
15	29.5	30.5	30	25.5
17	30.1	31.3	30.7	26.2
19	31	32	31.5	26.9
21	31.7	32.3	32	27.4

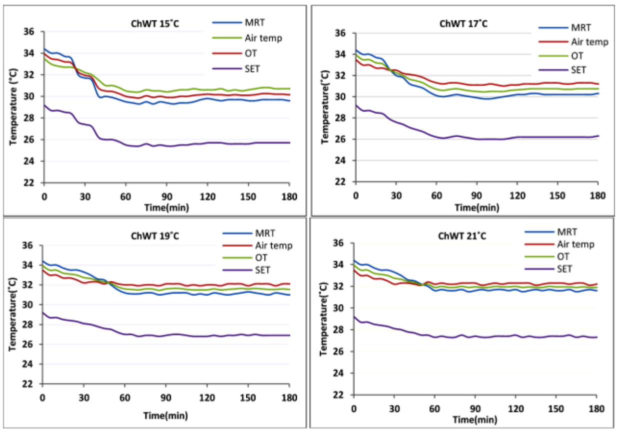

Figure 4: Variation in indoor temperatures in case of RCCS

It is observed from the graph that for all cases, initially MRT was greater than air temperature but achieving stability in temperature; MRT becomes lower than air temperature. This indicates that on higher air temperature occupant feels low temperatures because of the radiant cooled surface.

The reason behind low MRT is the less ceiling temperature compare to another wall in the room. It also caters some of the solar heat gains which ceiling absorb from the sun radiation. Hence radiation heat transfers between the occupant and cooled surface increases.

Personalized Radiant Conditioning System (PRCS):

For Case-2, Personalized Radiant Conditioning System has been run on different supply water temperature i.e. 15°C to 21°C. During the experiment, the dehumidifier was constantly running to maintain the RH level of the room at 40%. A tower fan is also running during the test to maintain air velocity 1 m/s near the occupant. Table 2 shows the measured and calculated parameters.

Table 2: Variation in different indoor temperatures

Chilled water temp. (°C)	MRT (°C)	Air temp (°C)	OT (°C)	SET (°C)
15	27.5	27.8	27.7	23.4
17	28.6	29.1	28.9	24.5
19	29.5	29.9	29.7	25.2
21	31.5	31.8	31.7	27

Figure 5 shows the graph of time and temperature for different chilled water temperature.

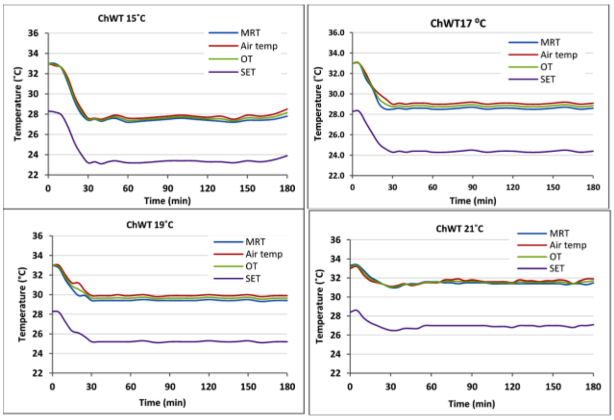

Figure 5: Variation in indoor temperatures in case of PRCS

Inferences from Graph:

- The difference between MRT and the air temperature was found less than 1°C which states high thermal comfort within the region.
- It is observed that background temperature is quite high compared to a temperature in PRCS proximity area because of the cooling provided in the vicinity of occupant only. The background temperature was still in the comfortable range.

PRCS cater sensible heat load only in its proximity area so unable to cater the background load. Thus, background temperature was found higher than the PRCS area.

Combined PRCS and RCCS

For Case-3, both PRCS and RCCS have been run simultaneously. The reason behind running simultaneously was to maintain thermal comfort in PRCS zone and maintain suitable background temperature outside the PRCS zone. During the experiments, both systems were run on the same supply water temperature. Measured and calculated parameters shown in Table 3.

Table 3: Variation in different indoor temperatures

Chilled water temp. (°C)	MRT (°C)	Air temp (°C)	OT (°C)	SET (°C)
15	27.2	27.7	27.4	23.1
17	27.6	28	27.8	23.5
19	28.3	28.5	28.4	24
21	29.9	30.8	30.4	25.9

Figure 6 shows real performance of the combined system on different supply water temperature.

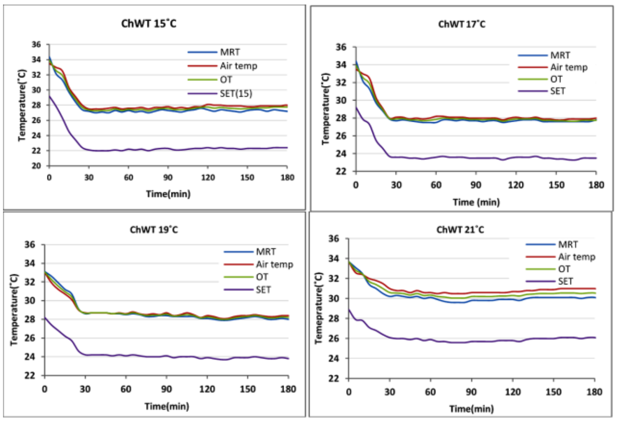

Figure 6: Variation in indoor temperatures in case of combination of PRCS & RCCS

The inference from the Graph:

- MRT was less than the air temperature & their difference was less than 1°C because of the more radiant cooled surface area, and this leads to better thermal comfort.
- The time taken by MRT to overcome the air temperature is very less compare to others because of a large amount of radiant surface area.
- Background temperature also maintained a significant level by the RCCS.

Spatial Distribution of Temperature

Spatial distribution of temperature plays a significant role in the thermal comfort. It defined as a vertical air temperature according to height. As per the ASHRAE standard 55, the vertical air temperature should not be more than 3°C in the case of a radiant system. Higher temperature difference leads to the thermal discomfort. The air temperature was measured at four different heights i.e. 0.1 m, 0.6 m, 1.1 m & 1.7 m to analyze the spatial distribution. Figure 7(a,b,c) represents the spatial distribution of air temperature at the different height of the room for all three cases.

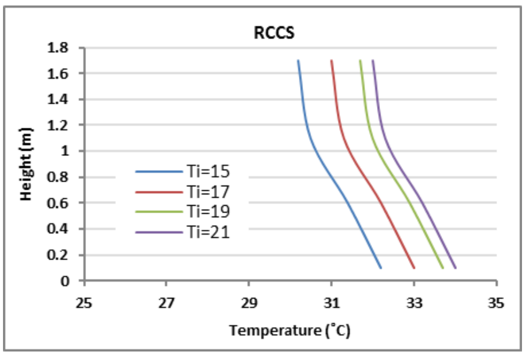

Figure 7(a): Spatial Air Distribution in case of RCCS

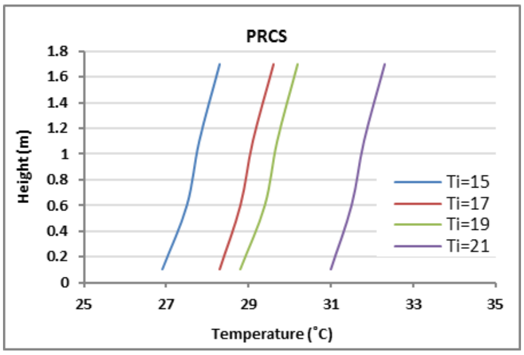

Figure 7(b): Spatial Air Distribution in case of PRCS

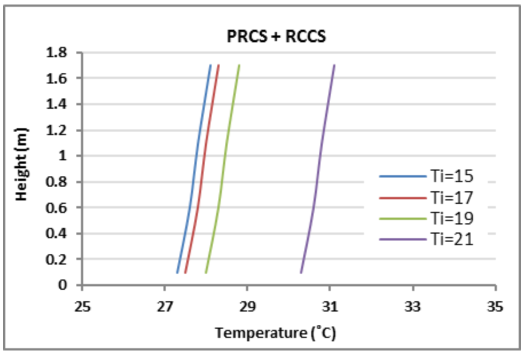

Figure 7(c): Spatial Air Distribution in case of combination of PRCS & RCCS

In the case of a combination of PRCS & RCCS, vertical air temperature varies very less due to uniform MRT and proper distribution of air. While in another case, the variation is a little high due to uniform distribution of air in the vicinity of occupant only because of radiative heat exchange.

Thermal Comfort Analysis

SET is one of the comfort indices for the study of thermal comfort because it takes care of both environmental and personal factors. Dhaka (2015) described in his field study for conditioned buildings that occupants feel comfortable in the SET range of 23°C to 26°C for the composite climate. For analysis of thermal comfort, above SET range has been taken as the reference for all cases. Figure 8(a,b,c) shows the SET variation of different cases. In these figures shaded area shows the thermal comfort region as per the literature.

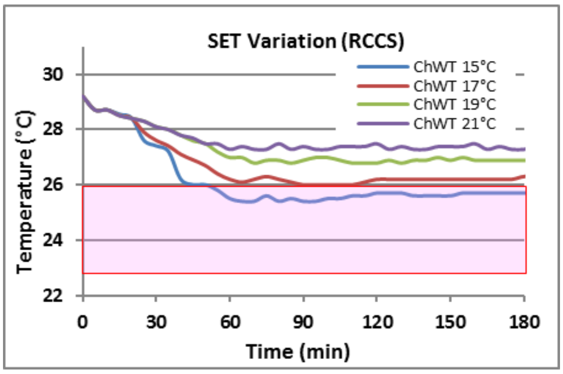

Figure 8(a): Variation of SET at different chWT for RCCS

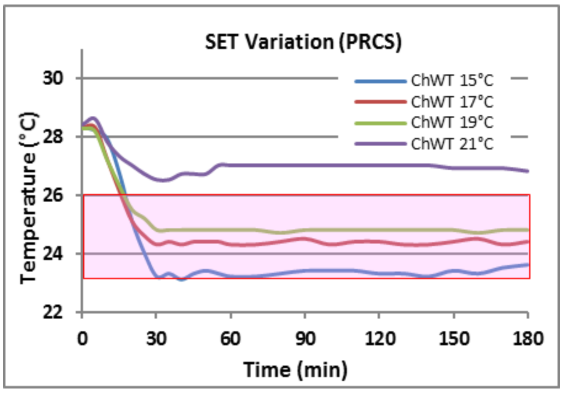

Figure 8(b): Variation of SET at different chWT for PRCS

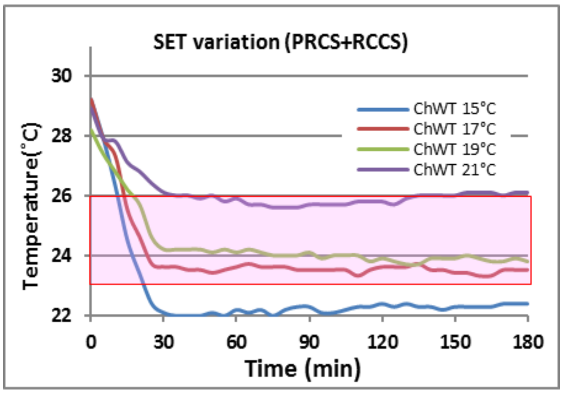

Figure 8(c): Variation of SET at different chWT for PRCS & RCCS

In the case of RCCS (figure 8a), thermal comfort achieved only when supply water temperature was 15°C because of the slow uniform distribution of air in the whole room.

In the case of PRCS (figure 8b), achieved a thermal environment in the vicinity of the occupant was well within the thermal comfort range for almost every range of supply water temperature i.e. 15°C to 19°C. As the supply water temperature increases, the thermal energy consumption decreases.

In the case of a combination of PRCS and RCCS (figure 8c), SET was in comfort criteria when supply water temperature was in the range between 17°C to 21°C. The thermal comfort achieves on the higher range of supply water temperature indicates the good thermal efficiency of the system and its lower energy consumption.

An interval plot has been drawn from all three cases for SET with supply water temperature range from 15°C to 21°C. Figure 9 represents the thermal comfort region on the basis of SET for all radiant cases.

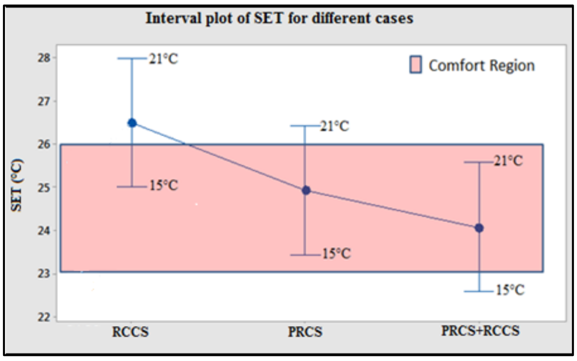

Figure 9: Thermal comfort region in different cases

It can be stated from the graph that:

- Case 1: The average SET was found above the comfort region for different supply water temperature. In this case, only 15°C supply water temperature was able to maintain the thermal comfort, and if the water temperature further reduces, there will be a problem of condensation which will not be a favorable condition regarding energy.
- Case 2: The average SET was achieved for almost all of the supply water temperature except 21°C, but it was not able to maintain the background temperature of the room because of cooling occurred only in the vicinity of the occupant.
- Case 3: When system run with a combination of both PRCS and RCCS, the thermal comfort achieved was better than other cases even when supply water temperature maintained at high temperature.

Energy Consumption Analysis

Energy consumption analysis has been carried out for all three cases by measuring thermal energy. For all the cases thermal energy was measured by BTU meter and further converted into electric energy taking the assumption of COP 3. According to ASHRAE Standard 55, one person should occupy $10m^2$ floor area so for energy analysis of PRCS; two cubicles were assumed as total floor area was $18m^2$. So, for this analysis, energy consumed by PRCS was considered as double of its actual energy consumption. Figure 10 represents the electric energy consumption for one reference SET of all three cases.

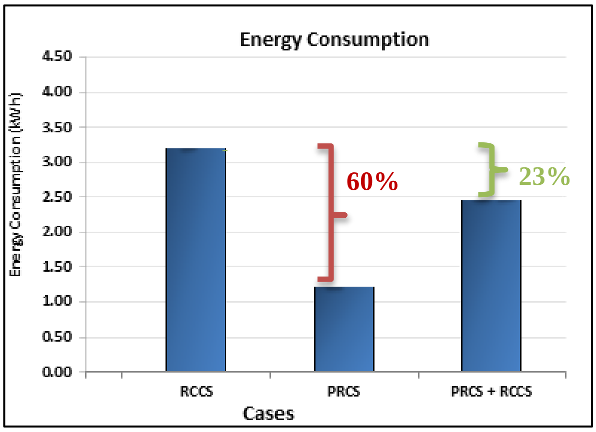

Figure 10: Comparison of Energy Consumption

The energy consumption of PRCS is minimum compared to other existing cases because it conditioned less area to compare to other cases. In the case of the combined system of PRCS and RCCS the thermal comfort was achieved on higher supply water temperature hence its energy consumption is reduced compared to the only RCCS.

For the same level of thermal comfort in the occupied zone, 60% energy saving has been achieved for PRCS over RCCS. When a combination of PRCS and RCCS was run, the saving achieved was 23% compared to RCCS.

Response Time Analysis

Response time is the time required by the system to achieve the thermal equilibrium in the conditioned space. The more response time will be, the more time to achieve thermal comfort, so less response time is always recommended in HVAC systems. Only one supply water temperature was considered from each of the cases to find out the response time for the systems. The reason for taking only one supply water temperature for each case was the minimum energy consumption while maintaining the same level of thermal comfort. Figure 11 represents the response time of reference cases of different regimes.

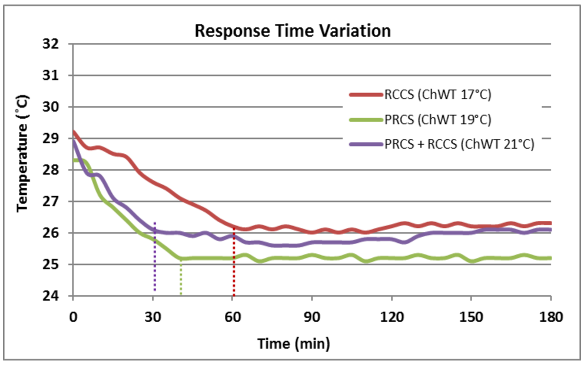

Figure 11: Response time of reference cases for different cases

The response time of PRCS system was around 40 minutes which is better than RCCS. For the combination of PRCS and RCCS, it was only 30 minutes which is better than both individually PRCS and RCCS. In the case of RCCS, cooling takes place at high water temperature. The response time of combined system was lesser than others because of circulating air and more cooled surface area.

Conclusions

An individual approach to the building occupants makes it possible to satisfy different needs of different persons and thus improves comfort & subsequently performance. Personalized Radiant Conditioning System in an office has been developed to fulfill the individual thermal comfort requirement. To evaluate the performance for PRCS in cooling mode, three different cases have been developed which includes Radiant Ceiling Cooling System (RCCS), Personalized Radiant Cooling System

(PRCS), Combination of Ceiling Radiant System and Personalized Radiant Cooling System. Experiments were performed for different chilled water temperature with maintaining the performance parameter i.e. Standard Effective Temperature for each case. The main conclusions of this study were:

- For cooling mode, PRCS was able to provide sufficient cooling for supply water temperature range within 15°C to 19°C and maintain thermal comfort in the vicinity of the occupant but was unable to uphold the background temperature to a comfort level. When PRCS was coupled with RCCS, thermal comfort achieved at higher supply water temperature with maintaining the background temperature. The SET was achieved on supply water temperature ranging from 17°C to 21°C.
- For cooling mode, energy consumption was compared to all the cases on RCCS; significant saving achieved i.e. 60% for PRCS and 23% when combined with PRCS and RCCS.
- Response time was found to be good i.e. 45 min in case of PRCS because of the less cooling area. The combination of PRCS & RCCS shows the best response time in all of the cases.

This study proved that the PRCS could fulfill the requirement of thermal comfort in an efficient way and when combined with Radiant Ceiling Conditioning System, it gives better thermal comfort and energy saving.

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