PERFORMANCE EVALUATION OF CEILING RADIANT COOLING SYSTEM IN COMPOSITE CLIMATE

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ABSTRACT

Radiant cooling systems are proving to be an energy efficient solution due to higher thermal capacity of cooling fluid especially for the buildings that require individual zone controls and where the latent loads are moderate. The Conventional air conditioners work at very low temperature i.e.5-8^{0}c (refrigerant evaporator inlet) while the radiant cooling systems, also referred as high temperature cooling system, work at high temperatures i.e. 14-18 ^{0}c. The radiant cooling systems can maintain lower MRT (Mean Radiant Temperature) as ceiling panels maintain uniform temperature gradient inside room and provide higher human comfort. The radiant cooling systems are relatively new systems and their operation and energy savings potential are not quantified for a large number of buildings and operational parameters. Moreover, there are only limited numbers of whole building simulation studies have been carried out for these systems to have a full confidence in the capability of modelling tools to simulate these systems and predict the impact of various operating parameters. Theoretically, savings achieve due to higher temperature set point of chilled water, which reduces chiller-running time. However, conventional air conditioner runs continuously to maintain requisite temperature. In this paper, experimental study for performance evaluation of radiant cooling system carried out on system installed at Malaviya National Institute of Technology Jaipur. This paper quantifies the energy savings opportunities and effective temperature by radiant cooling system at different chilled water flow rates and temperature range. The data collected/ analysed through experimental study will used for calibration and validation of system model of building prepared in building performance simulation software. This validated model used for exploring optimized combinations of key parameters for composite climate. These optimized combinations will used in formulation of radiant cooling system operations control strategy.

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INTRODUCTION

In today's era of energy crisis, providing comfort in buildings with energy efficient technologies has become a necessity. In India with new construction and infrastructure changes, demand will grow by 6.6 % in 2020. As per data, 70 % of the building area falls under space cooling (Kumar, Benchmarking energy use in building and cleanrooms, 2011). About 32 % of energy use of a commercial building comes under space cooling and this percentage rises to 45 % for residential buildings (Bureau of Energy Efficiency, 2006).

The integration of new installation concepts within the building design can reduce the energy consumption of the built environment together with an increasing quality of the indoor environment. A potential concept is the application of Radiant Cooling system. The available information regarding the performance of radiant cooling systems indicates that these systems not only reduce the energy consumption and peak power demand due to space conditioning, but that they also provide draft-free and noise-free cooling, reduce building space requirements

The radiant cooling system treats cooling load individually, directly and with more uniformity and thus improves thermal comfort (Imanari T., 1995). The energy performance of the radiant systems is better than the conventional systems. Tian et al., (Love, July 27-30, 2009) through a simulation-based study has demonstrated that the radiant slab system provided 10% to 40% better energy performance depending on the climate type. The best performance was achieved in dry climates.

(Stetiu, 1999) used a one-zone model to compare the energy performance of radiant cooling and conventional VAV systems for a typical summer week across a range of climates within the United States. It was reported that radiant cooling provided cooling energy use reductions of 17% to 42% relative to the conventional variable air volume (VAV) system.

Radiant Cooling has been one of the efficient cooling solutions, which has been in use in European countries for quite some time now. It is not a complex system of providing space cooling but making it widely accepted and providing controls for its proper functioning is and will always be a challenge. Though radiant cooling got its market acceptance in 2000 (Robert Bean, 2010), in India it has just arrived and people are uncertain about the functioning of the system in different climatic conditions of India. As per literature survey it was found that radiant cooling can save up to 40 % of energy over conventional system. Many research studies of Asian region show that radiant systems are working successfully in commercial as well as residential buildings.

As per studies conducted earlier and personal experience of people, radiant systems are much superior to conventional system in terms of thermal comfort. Cooling system's task is to provide better thermal comfort conditions in a zone; the moment there is any deviation in comfort parameters the system's existence comes in to notice. Radiant cooling system brings down the mean radiant temperatures (MRT) of the zone thereby lowering the zone operative temperature (OT) and effective temperature (ET). It also maintains the uniform temperature throughout the height of the zone. This improves the thermal comfort of the occupants significantly without increase in HVAC energy demand.

Conventional air cooling systems operate on mean air temperature (MAT) set points and do not rely on MRT for the set point operations. This not only increases the load on the system and thus increase energy consumption but also does not provide the uniform thermal comfort in the zone. There are several parameters which impact the energy consumption and thermal comfort in radiant cooling systems. In this paper a set of parameters of a radiant cooling system and their impact on energy consumption and thermal comfort has been investigated through an experimental setup.

In figure 1, energy consumption pattern of radiant and conventional system is shown. This data was monitored during comparison study of conventional and radiant system on same setup described in next paragraph. In figure, conventional system is continuously consuming energy, however, radiant system is consuming intermittently, which shows the energy saving opportunities in radiant system. During non-operation of chiller only recirculation pump was consuming energy.

To evaluate the energy savings and thermal comfort, a ceiling radiant panels system was fitted with several sensor, logger and energy meters for analysing the effect of these ceiling panels at different flow of chilled water.

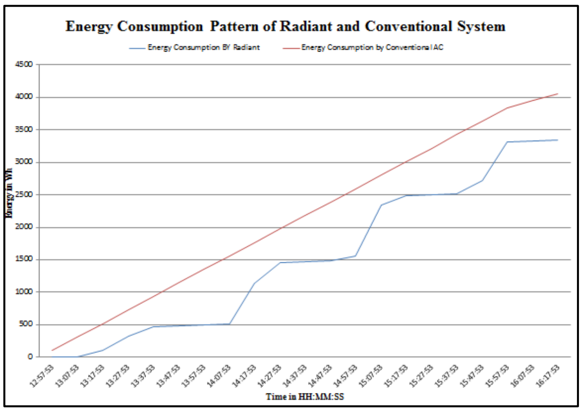


Figure 1- Energy Consumption Pattern of Radiant and conventional system

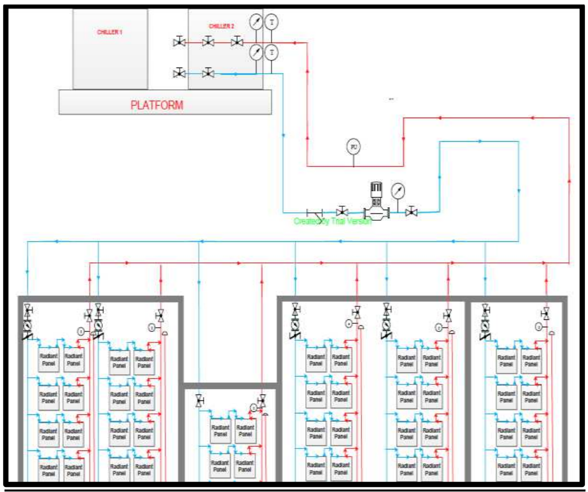
This experimental data will be used for a detailed building modelling and simulation study. The data will help in the calibration of building model as per the ambient conditions. In this experiment, two key parameters have considered;. Chilled water temperature & Chilled water flow rate. The building model and system will be calibrated by this experimental data through key parameters. This calibration helps in validation of the model and simulation results. After validation of model, annual energy savings and human comfort will be predicted using building simulation software. In addition, the calibrated model helps in exploring other optimized combination vis-à-vis preparation of control strategy of ceiling based radiant cooling system in composite and other climate zones.

EXPERIMENTAL SETUP

The experimental setup has been installed at second floor of Administrative building of Malaviya National Institute of Technology, Jaipur. This system consists of 4TR chiller for cooling chilled water and a Grundfos magna pump for recirculation of chilled water in the system/panels. The final setup of the system is shown in figure 2.

Figure 3 shows legend of the equipment's used in figure 2. These figures show the final arrangement of the ceiling radiant cooling system and its accessories. The chiller and recirculation pump have fitted on terrace of the building. The ceiling panels have fitted in the rooms. Piping system has Tichelmann system for piping arrangement. In this system a two-string system, where each panel and its auxiliary piping on the same floor has the same total distribution pipe length (supply + return – measured from the pump through the panels and back to the pump) is called a Tichelmann system. It is also commonly referred to as a reverse return system.

Instrumentation & Measurement



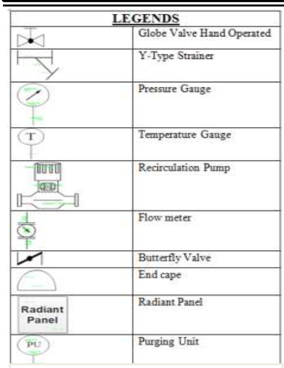


Figure 3- Legends

Figure 2- System Layout

Table 1 shows the measuring performance parameters along with the measured parameters such as water & air temperature, humidity, air velocity and mean radiant temperature (MRT) and measuring sensors/instruments.

These sensors have been selected based on the literature review {(Francesco Causone, 2009), (Rongling Lia, 2014), (S.P. Corgnati, 2008), (Jingjuan (Dove) Feng, 2014), (Fonseca, 2011), (K. Nagano, 2003), (Cui Yong, 2014), (Nipaporn Nutprasert, 2014), (Tan Chun Lianga, 2014)} and in-house availability of sensors.

Table 1- Instrumentation & Measurement

Sl No	Equipment (Working limit)/ Parameters	Units	Measuring Instruments	Accuracy
1	Chiller (14 to 20 °C)	kWh, kW	Fluke Energy Analyzer	± 0.001 kWh
		Main header Supply & return chilled water temperature (°C)	Analog gauge	± 1 °C
		Main header Supply & return chilled water pressure (kg/cm²)	Analog gauge	± 0.2 kg/cm²
2	Recirculation Pump (Inlet temperature -10 to 110 °C, Pressure 10 bar, ambient temperature 0 to 40 °C)	kW (kWh to be calculated)	Pump local display	± 1 W
		Pressure head	Pump local display	± 0.1 m
		Flow rate	Pump local display	± 0.1 m³/hr
3	Conventional air conditioner (18 to 30 °C)	kWh, kW	Fluke Energy Analyzer	± 0.001 kWh
4	Room indoor temperature	Temperature °C	HOBO Make Temperature sensor (Thermistor type)	± 0.35°C
		Relative Humidity %	HOBO Make (Type Capacitive	±2.5%
		Mean Radiant Temperature	Globe	±0.5°C
		Temperature °C	Thermocouple	±0.1°C
5	Radiant ceiling panel	Temperature °C	Thermocouple	±0.1°C
6	Ambient air	Temperature °C	Thermistor Type	± 0.35°C
		Relative Humidity %	Capacitive type	±2.5%
7	Inline chilled water temperature	Temperature °C	PT 100	±0.1°C

Placement of Sensors

Above mentioned sensors and loggers have been fitted in a particular order shown in Table 2. The location of measurement have been selected in accordance with ASHRAE 55 2004 section 7.2.2.

In figure 4 and 5 placement of sensors have shown for positioning of the temperature sensors i.e. HOBO and thermocouples. Thermocouples used to measure the surface temperature of panel, these sensors are placed in centre of the panel by double side tape for maintaining good sticking with insulation from indoor conditions. Temperature sensor measuring indoor air condition is place as per ASHRAE 55 standards at 1 meter away from the wall at 1.2 meter

Table2- Placement of Temperature sensors

Sl No	Place of fitment	Sensor Details	
		Temperature Logger 'Type Thermistor' (Make – HOBO)	Thermocouple Sl. No
1	0.6 m above Panel in Vertical Stand	B1	
2	0.1 m above Panel in Vertical Stand		13
3	0.1 m below Panel in Vertical Stand	B2	
4	1.7 m above Floor in Vertical Stand	R1	
5	1.1 m above Floor in Vertical Stand	R3	14
6	0.6 m above Floor in Vertical Stand		15
7	0.1 m above Floor in Vertical Stand		16
8	South Wall	R4	
9	East Wall	R5	
10	North Wall	R6	
11	West Wall	R7	
12	Row 1 supply 1 panel 1		1
13	Row 2 supply 1 panel 2		2
14	Row 1 supply 2 panel 1		3
15	Row 2 supply 2 panel 2		4
16	Row 6 supply 1 panel 2		5
17	Row 5 supply 1 panel 3		6
18	Row 6 supply 2 panel 3		7
19	Row 5 supply 2 panel 4		8
20	Row 3 supply 2 panel 1		9
21	Row 3 supply 2 panel 2		10
22	Row 3 supply 2 panel 3		11
23	Row 3 supply 2 panel 4		12

height of the floor. HOBO sensors are having inbuilt logging arrangements and for thermocouples ATOMBERG make loggers have been used.

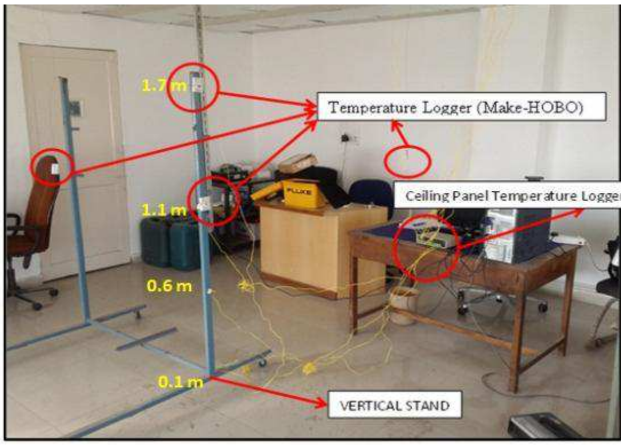


Figure3- Temperature sensor placement

To measure the indoor air temperature at different heights, in house stand was prepared. Requisite sensors were placed as per the guideline.

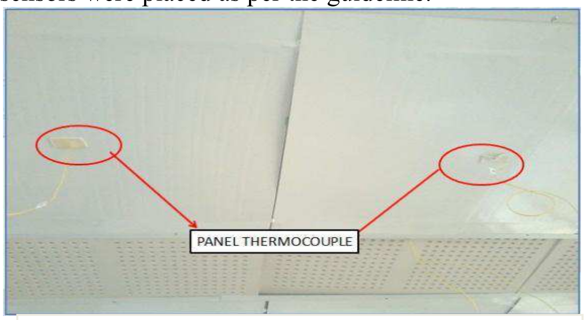


Figure 5- Surface Thermocouple placement

METHODOLOGY

In this experimental study, three variables that affect the performance of the ceiling radiant cooling system have been identified. These variables are **chilled water temperature**, **flow rate of chilled water** and internal loads. The values of chilled water temperature and flow rate was varied from the designed to 25 % higher & lower to ascertain the performance of the system. To analyse the effect of above-mentioned variables various combinations have used. Those combinations have been shown by different abbreviations, in that 1st two letter **i.e.** T1 Stands for temperature setting of chiller at which chilled water is cooled from 15 to18.5 ^{0}C, T2 (14 to 17.5 °C) & T3 (16 to 19.5°C), 2nd two letter **i.e.** LF – Stands for flow rate – Low/ High/ Designed Flow rate, 3rd two letter **– i.e.** FL – Stands for Loading condition of indoor – Full/ Half/ Partial loading**.** For internal loads, six 100 W bulbs were used as a sensible load. Six occupants were assumed in the room and each bulb represent an occupant. In the partial loading condition, one person is sitting inside the room to monitor the flow, temperature and energy meter logging.

In the experiment, various combinations of energy consumptions, panel temperature, indoor temperature & RH (Relative Humidity) at different directions & different heights, flow rate of chilled water with chilled water temperature and MRT was measured. The effective temperature was calculated with the help of above-mentioned parameters (C. Bouden, 2004)**.** The ET is defined as that temperature at 50% relative humidity, and mean radiant temperature equal to air temperature, that would produce the same thermal sensation as the actual environment. In other words, ET normalizes temperatures for humidity and radiation thereby facilitating comparison of various parameters with a single index Different combinations have compared based on similar ambient conditions. In the experiment 2-3 ° C, temperature variation in ambient is consider similar condition for comparison. After logging all the parameters, analysis for different combination have carried out and shown in result and discussion section for selecting better combination.

RESULT & DISCUSSION

As seen in figure 6, the ambient temperatures for various combinations of experiments, are in the range of 2 to 4 °C, therefore, it is assumed that similar ambient conditions existed for all the combinations.

After considering similar ambient conditions, comparison based on effective temperature was carried out. In figure 7, comparison of effective temperature is shown. It is observed from figure 7 that minimum ET has achieved at T1-DF-FL combination, and maximum achieved at T1-LF-FL However, in case of reduced chilled water temperature range i.e. T2, ET of all the combinations are lesser than T1 chilled water range and under human comfort limit except at designed flow rate of T1.

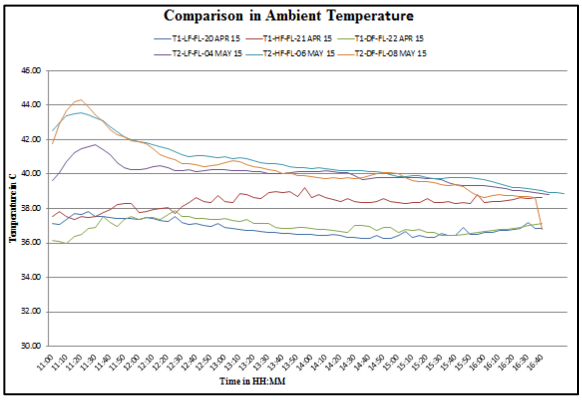


Figure 6- ambient temperature comparison

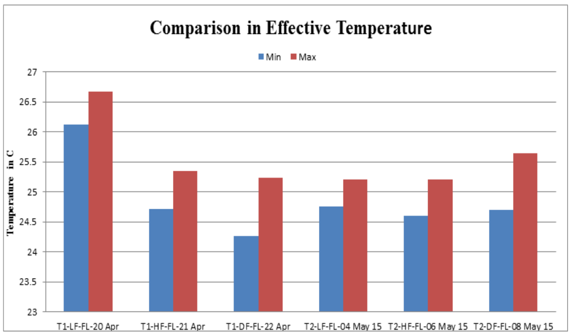


Figure 7- Effective Temperature comparison

Further, deciding the optimized combination, energy consumption and refrigeration capacity in Wh consumed and provided by system at different combinations is analysed for an hour in figure 8 respectively. Here, energy consumption consists of recirculation pump, chiller fan and compressor energy consumption and refrigeration capacity calculated by following equation:-

$$\text{Net refrigeration capacity (TR)} = \frac{m \times c_p \times \Delta t}{3024}$$

Where, **m** is mass flow rate of chilled water in kg/hr

$\mathbf{c_p}$ is specific heat in kcal/kg °C

$\Delta t = t_{out} - t_{in}$ = change in chilled water temperature.

$\mathbf{t_{in}}$ is Chilled water temperature at system inlet in °C

$\mathbf{t_{out}}$ is chilled water temperature at system outlet in °C

However, in this figure, in energy consumption T1 range combinations are better than the T2 range. However, in respect of refrigeration capacity provided by T2 range system is better than T1. Therefore, selection of combination is depends upon the priority of user i.e. required higher comfort selection will T2, otherwise T1.

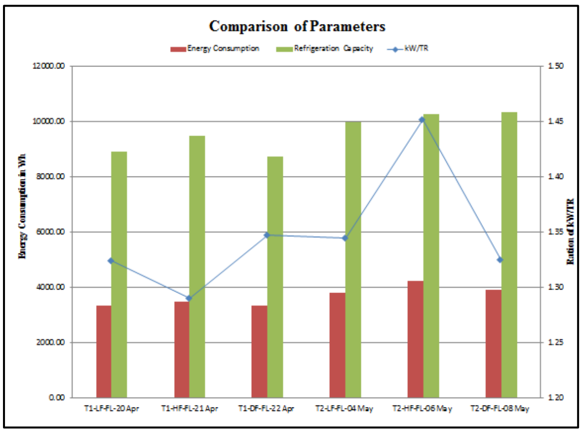


Figure 8- Comparison of parameters

In this figure, due to change in chilled water temperature range (from T1 to T2) energy consumption and refrigeration capacity have increased to 37.73% and 18.47% respectively, this % is showing difference between maximum to minimum values.

Above parameters do not able to help in selecting better combinations; therefore, kW/TR (Kilo Watt/ Ton of Refrigeration) values are also shown in figure 8. The lowest value of kW/TR is achieved by T1-HF-FL and other T1 combination values i.e 1.32 is lesser than their T2 i.e. 1.34 counterpart. Therefore, the condition of selecting optimized combination is purely depends upon user requirement and priority.

Again, to select the optimized combination with energy savings, COP (Coefficient of Performance) of this system calculated from refrigeration capacity divided by energy consumption and shown in figure 9. In this figure minimum COP is at high flow rate of T2 temperature span and maximum at high flow rate of T1 temperature span. However, for other four combinations COP of system has more or less similar. The maximum difference in COP of lower and other four combinations is 12.3%. Therefore, selection of optimized flow rate can chose from remaining combinations.

In the ceiling radiant cooling system condensation is a major problem. To protect system from condensation, in this experiment dew point temperature (DPT) of indoor air was calculated. In figure 10, temperature difference between panel temperature and dew point temperature of indoor air are shown, which clearly negates the condensation situation in any of the combination.

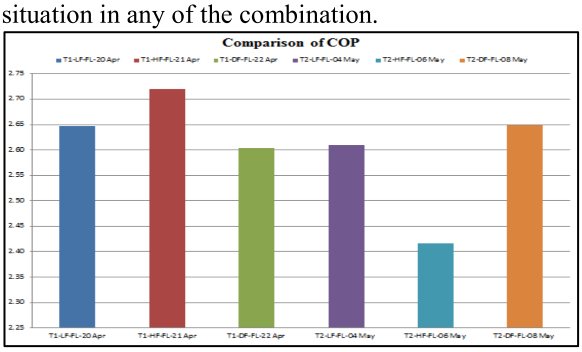


Figure 9- Comparison of COP

In following figures, panel temperature comparison has shown at different combinations. In these figures different panel surface temperatures has monitored at time. In figure 11, panel surface temperature at low

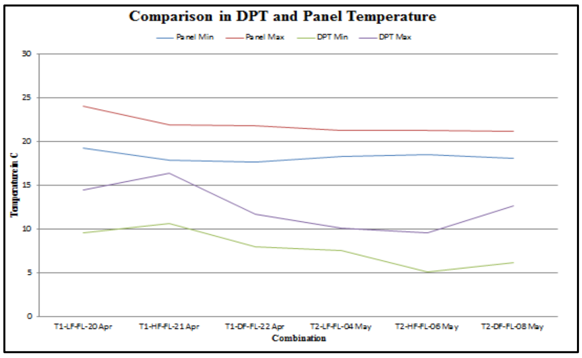


Figure 10- Comparison in DPT and Panel Temperature

flow rate with full load has shown, in that at 1500 hours, spike in temperature can observed, which was outcome of supply interruption for 5 min, in this period chiller and recirculation pump were switched off. Therefore, this figure is considered as indication of supply interruption or tripping of pump or chiller. This figure shows system sensitivity co-relation with parameter that will used for control strategy as fault detector.

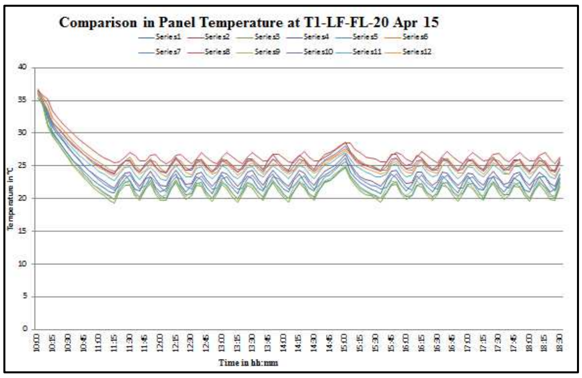


Figure 11- Comparison of Panel surface Temperature at various points

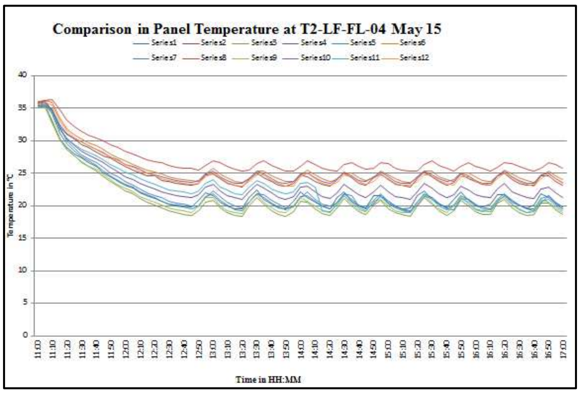


Figure 12- Comparison of Panel surface Temperature at various points

In figure 11 and 12, comparison between T1 and T2 combination at low flow rate with full load have shown. In these figures, chiller running time can be calculated as the temperature reduces from the peak temperature to least one. It is clearly observed that number of ON and OFF are more in T1 period. However, time required to reach least temperature and stablized zone, after chiller start temperature were more due to lower chiled water temperature range of T2. In the same way, panel surface temperature at high flow rate and designed flow rate were monitored and showing the same pattern except high flow rate combination of T1 and T2 chilled water range where output variation of kW/TR is significant due to variation in ambient temperature and reduction in chilled water temperature set point. These figures are depicting starting & stopping of chiller during running of system and minimum temperature achieved on panel surface.

PREPARATION OF MODEL The model in Energy Plus has created with the help of dimensions & construction specification of lab room and building, also included system specification provided by the system installer. This model is required to be validated with help of experimentation carried out in this paper for further use of this model for different climatic condition. In this model all the real conditions of room have used to predict approximately similar conditions. In this model, only sensible loading case is considered, here latent loading is not included. Also, the whole roof is considered as a series of radiant panels fitted in rows.

SIMULATION OF MODEL The model has simulated in Energy Plus, in this model all the parameters have selected as per the design requirement conditions. In this paper, three conditions have indicated, one chilled water temperature variation, thereafter flow rate and then loading condition inside the room i.e. sensible loading. The validation of model is in progress to get the exact results as per the experimentation results. As soon as this model is validated, the same may be used to get the output of the various climatic condition for similar configuration of system, also it can be scale up as per the changes in the configuration of the system.

CONCLUSION

This paper concludes that, for quantification of better combination, various aspects have to be analysed. In this experiment, newly fitted ceiling radiant cooling system at different combinations have been analysed and found that for specific condition i.e. flow rate or chilled water temperature, there might be a single optimized combination and may not be a set of combinations can provide similar human comfort with energy savings. In this experiment, full loading of indoor condition is considered for deciding optimized combination.

Following considered as optimized combination from this experiment:-

(a) Lowest ET and energy consumption at T1-DF-FL
(b) Lowest kW/TR and highest COP at T1-HF-FL
(c) Optimize ET and kW/TR at T1-HF-FL.
(d) Maximum DPT and panel temperature difference achieved at T2-HF-FL. It means there is a scope of lowering chilled water temperature range that can able to further lower ET for better human comfort.

These experimental results will be used in building performance simulation software to calibrate and validate the model in software. This will help in ascertain the performance of the system in whole year. After calibration and validation of model, it will use for exploring other optimized combinations for higher energy savings and better human comfort on not only composite climate but also in other climatic conditions. In this experiment a key parameters has not considered i.e. load it can be sensible, latent or both. There might be case of full, half and partial loading, which can be consider in future experiment for better optimization of combinations as per the human comfort. This paper can be considered as an initial proposal for preparation of control strategy and search of optimized combinations for different system variations of ceiling based radiant cooling system in composite and other climate.

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