Radiant Cooling: A Case Study of Energy Savings and its Enhancement in an Office Building

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ABSTRACT
The paper presents the assessment of energy savings of a radiant cooling system installed in an Information Technology (IT) office building in a composite climate of Hyderabad, India. The radiant system consists of both floor and roof mounted tubular installations and is coupled to a Fan Coil Unit (FCU) to meet the latent load requirements of the conditioned space. Based on the building characteristics, system parameters and a few modeling assumptions, the thermal performance and energy consumption of the building was simulated using ANSYS FLUENT and EnergyPlus software. To ensure the accuracy of the building energy model, it was calibrated using the measured data. The calibrated building energy model was modified, by replacing the current radiant cooling system with a conventional all air system, for comparing the performance of these two HVAC systems. To further study the additional energy savings potential of the existing radiant cooling system, the simulation was carried out by replacing the FCU's with an integrated Dedicated Outside Air System (DOAS) and Heat Recovery Wheel (HRW) in of the calibrated model. The results show 21% energy savings of radiant systems over conventional system and an additional potential of 15% savings using DOAS in place of FCU.

KEYWORDS
Radiant Cooling System, Building Energy Simulation, Energy Saving, EnergyPlus, CFD.

INTRODUCTION
Cooling of buildings equipped with 'All-Air' Systems contributes substantially to the electrical energy consumption and to the peak power demand. In India such systems typically consume 32-55 % of energy depending on the building type and operating hours. [1]

Amongst conditioning systems, the vapor compression based all air systems are widely used. These systems have multiple fans as a subcomponent for circulating large volume of air and it consumes approximate 35-40 % energy of the total consumption of HVAC system. [2] In comparison, the radiant cooling systems separate the thermal conditioning and ventilation need. Thus the volume of air moved and the associated components to move it can be roughly five times smaller; also Fan power is saved and ducts can be smaller. In addition, the supply chilled water temperature in conventional air conditioning system has a typical range of 6-8 °C. However, in radiant cooling systems the supply water temperature lies typically in the range 15-18 °C and the temperature differential between supply and return is smaller ranging between 2-4 °C. [3]

Imanari et al., (1999) compared radiant ceiling panel systems with the conventional all air system by numerical simulation and reported that using radiant ceiling panel successfully reduced air transport energy by 20%, and thermal energy by almost 10%. As a result energy cost was reduced 10% by using radiant cooling system. [4]
These studies show that the radiant cooling systems have a large potential for energy savings in commercial buildings. The simulation models used may need hundreds of model inputs which have high degree of uncertainty because of software assumptions and imperfect field data collection processes. Therefore, accurate model predictions are not guaranteed, even if the underlying physical algorithms are accurate.
In this paper, a calibration approach has been used to predict and compare the performance of radiant cooling system and conventional all air HVAC system. The building energy model of an existing office building was developed using EnergyPlus software and the model was calibrated using the measured energy performance data. Additionally, the Computation Fluid Dynamics (CFD) model of the building was also developed to predict the thermal comfort.

EVALUATION APPROACH AND METHODOLOGY

The main objectives of this paper are to evaluate the energy savings of the radiant cooling system installed in an existing IT building as compared to the conventional all air HVAC system and study the potential further improvements in its performance in both energy and thermal environment perspective using simulation techniques.
To meet these objectives, three building energy models of the buildings were developed in EnergyPlus. The building energy model of existing radiant system has been termed as 'Actual Case' whiles the hypothetical conventional HVAC system has been referred as 'Conventional Case' and additional saving options as 'Advance case'.
The 'Actual Case' represents the existing radiant system in the building is coupled to FCU for meeting the latent load requirements. This model, calibrated with the measured data was simulated for energy performance. Thereafter, same cooling load was applied for the 'Conventional Case' which represents auto sized conventional central cooling system. The flow chart in Fig 1 represents the step by step procedure for comparative assessment of energy savings.

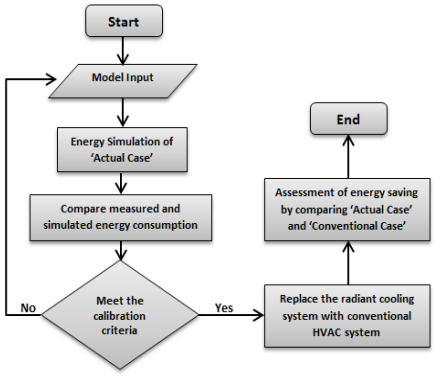


Figure 1- Flowchart of evolution approach 1

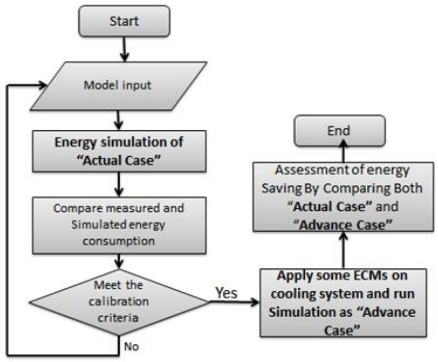


Figure 2- Flowchart of evolution approach 2

For the purpose of enhancing energy saving in the existing reference building, modifications were carried out in the 'Actual Case' by replacing fan coil unit with Dedicated Outdoor Air System (DOAS) coupled with Heat Recovery System (HRW). The complete step by step process is shown in the above figure 2.

The energy analysis was done using EnergyPlus while thermal performance was evaluated by using CFD software ANSYS FLUENT which can effectively model and analyze heat transfer applications.

BUILDING MODELLING

Development of 'Actual Case' Model

The modeled building is an IT office building of Tech Mahindra located at Hyderabad, India in a composite climatic zone and has a conditioned space of approximate 354 square meters. The building model created in EnergyPlus is shown in Fig 3.

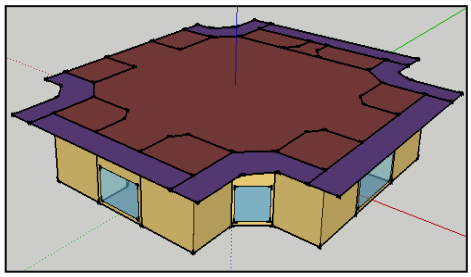


Figure 3- Building geometry model in EnergyPlus

A variable occupancy pattern in the range of 10 to 50 persons with 7 to 19 hours office presence during weekdays were considered in the simulations. No occupancy was considered during weekends. Based on ASHRAE guidelines, each person generates 115 W heats of which 70 W sensible and 45 W latent loads were considered for each occupant. [5] The other building construction and operation related parameters are as per Table- 1.

Table 1 Building Input Parameters

Building input Parameters	**Value**
Wall Construction	Brick wall with Both sides cement plaster (U-factor [W/m^2-K]= 1.870)
Roof Construction	Concrete Roof with outside cement plaster and inside Gypsum Plastering (U-factor with Film [W/m^2-K]= 1.054)
Floor Construction	Layer by Layer as Hard stone + EPS + Screed+ floor tiles (U-factor with Film [W/m^2-K]= 0.962)
Window Material Glazing	SHGC = 0.614, Conductivity = 5.714, VLT = 0.881
Window Frames and Dividers	Painted Wooden window frame with divided lite type divider
Window-Wall Ratio	E = 11.7%, W = 0%, N = 0%, S = 20% Building average = 8.02%
Overhang	2 meter
Internal Load	LPD [W/m^2] = 8.5, Plug Load [W/m^2] = 20, Occupancy = 50

HVAC System Configuration

Figure 3- Radiant ceiling cooling system

Figure 4- Radiant floor cooling system

The radiant cooling system comprises of both floor (Fig.4) and roof (Fig.5) versions which are integrated in the slab and caters to sensible cooling needs.

For the latent loads FCU's are provided which are coupled to a chiller which mainly serves to an adjacent building cooling load beside supplying chilled water to FCU's. The ventilation is thus provided by a constant volume FCU system functioning with 20% outside air only. The detail description of system configuration is given in the table 2.

Table 2 HVAC System configuration parameters

Parameter	Value
HVAC System Type	Radiant Floor and Ceiling System with Fan Coil Unit
Fan Design	Constant Volume with 0.85 m^3/s (1800 CFM)
Supply Air Temp Set Point	19-20 °C
Chiller Parameter	FCU Chiller autosized with 3.1 COP and 12 °C leaving ChW Temp Radiant Chiller 35 kW with 3.5 COP and 16 °C Leaving ChW Temp
Radiant Pipes Dia, Spacing & per Loop Length	Diameter = 15 mm, Spacing = 150 mm in ceiling, 100mm in floor, Loop Length = 4640 m
Ventilation	20% Fresh air of the total supply flow
Zone Set Point Temp	24 ^oC

The zone thermostat determines the FCU system operation and the radiant temperature schedule determines the response of the radiant system. Chilled water (ChW) flow varies linearly around the set point temperature. The fan pressure rise, fan efficiency and motor efficiency have been taken as 330 Pa, 52 % and 80 % respectively. [6]

Model Calibration and Validation

The general purpose of the model calibration is to achieve accurate and better simulation result that can match the measured data within good agreement. The US DOE Federal energy management program (FEMP) Measurement and verification guidelines (2004) provide some criteria for the calibration in terms of NMBE (Normalize Mean Bias Error) and CvRMSE (Coefficient of Variation of Root Mean Square Error) index. Acceptable tolerance for MBE and CvRMSE (FEMP, IPMVP) are listed in Table 3 below.

Table 3 Calibration Criteria

Calibration Type	Index	Limit		Calibrated Model Error
		(IPMVP)	(FEMP)	
Hourly	MBE	-	±10%	4.7 %
	CvRMSE	**20%**	30%	13.5 %

We didn't have a whole building energy consumption, but to provide same cooling load for both cases. Therefore, calibration was done by adjusting the occupancy and plug load (electrical equipment) pattern, which has highest diversity to match measured and simulated HVAC energy consumption on an hourly basis from April to June. Calibration results found to be well within the acceptable limits of the above listed criteria and thus are satisfactory.

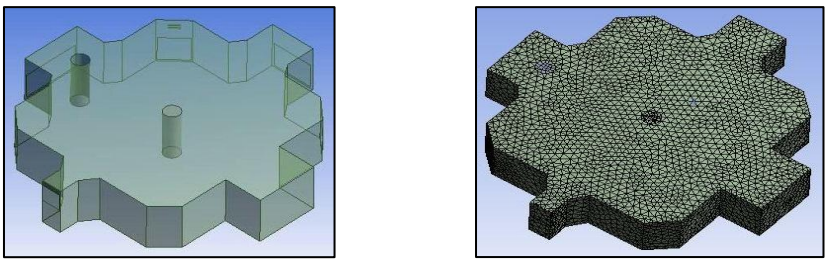
Development of Conventional Case

To estimate the energy saving of existing radiant cooling system a 'Conventional Case' has been modeled in which building construction and operational related parameters kept same but the existing cooling system is replaced by the central cooling system. To provide sufficient cooling, supply air temperature is reduced to 12-14 °C and switched the air system to auto-sized mode to maintain the cooling. Fan

design conditions have been modified as entire cooling load is handled by the air which requires more supply air flow. Chiller operating parameters were kept same because identical air cooled chiller was used which is providing the chilled water to adjacent building.

Development of CFD Model

In the analysis, geometry of the flow domain and mesh generation was built on the ANSYS's Workbench Platform. Numerical solution has been carried out with unsteady state implicit pressure based solver using FLUENT R14.5. Boundary condition for the flow from FCU's is specified as 'mass flow inlet' and 'pressure-outlet' condition for the return air supply duct. As the air flow is turbulent, k-ε model has been selected and S2S Radiation Model is used for the radiation heat transfer from walls. Physical and thermal properties of different engineering materials were used according to the material type. The building geometry and meshed drawing is shown in Fig. 6.



(a) Drawing of Building (b) Meshed Drawing of building

Figure 6: CFD Drawing of Building

CFD Model Validation

For calibration of model hourly readings of floor, roof temperature, supply air temperature and mass flow rate of air of FCU's has been taken from EnergyPlus model typically for the simulation done for April 09, 2013 from 8 am to 7 pm and applied to both the alternatives for CFD validation.

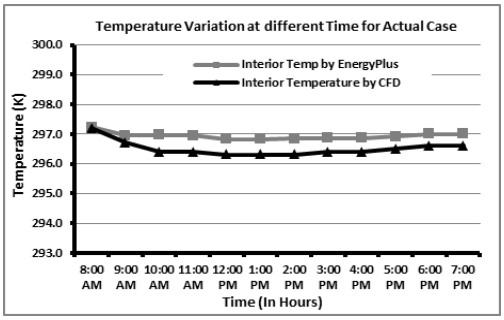


Figure 7- Temperature Variance (Actual Case)

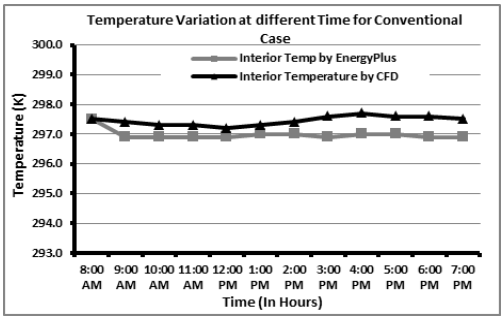


Figure 8- Temperature Variance (Conventional Case)

It has been observed that variation in simulated results of Air Temperature in CFD model and that of EnergyPlus shows a good agreement as shown in Fig.7 and Fig. 8. The marginal difference between the temperatures can be attributed to load dependent flow temperature variations. CFD model can thus be considered as a validated model for further performance analysis.

Development of the Advance Case

In order to handle condensation problem with cooling surface, a separate constant volume dedicated outdoor air system (DOAS) is modeled and integrated with the

existing radiant cooling system to provide the minimum amount of the ventilation air required by ASHRAE standard 62. The integrated system also consists of a heat recovery wheel (HRW). To maintain the lower dew point temperature in the zone, the outdoor air was dehumidified before entering the space and the supply air flow rate is just meet the ventilation requirement. All other operating and construction related parameters were taken same as in "Actual case".

RESULTS AND DISCUSSION

To compare the energy consumption of different cases hourly simulation has been done using the Typical Meteorological Year weather data of reference climate (composite) for April through June because the measured data available for this span only. The detail descriptions of case wise energy consumption are as follows-

Energy consumption comparison between 'Conventional Case' & 'Actual Case'

The analysis focus on the energy consumption while maintaining the reasonable unmet load hours (hours that don't meet the indoor set point temperature) limit. The unmet load hours for the actual case and base case are 24 and 4 respectively. So the difference between two cases is only 20 hours which fall within the criteria according to ASHRAE 90.1.

The energy consumption by components of the actual case with the conventional case is shown in fig 10. From result it has been shown that:

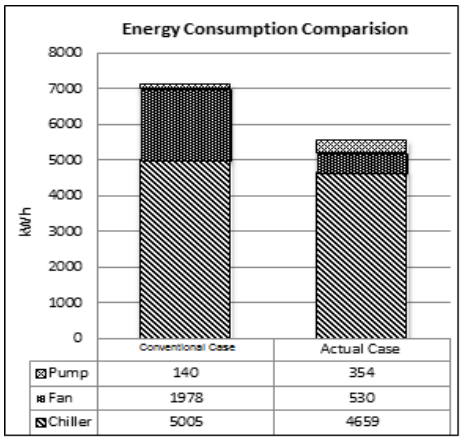


Figure 10- Energy consumption comparison of conventional and actual case

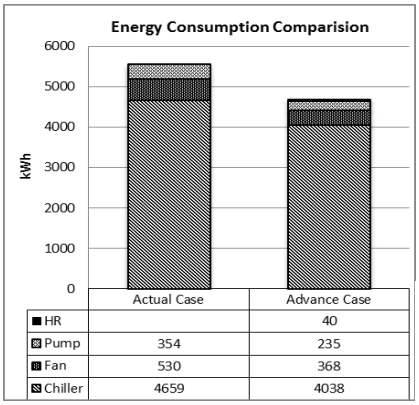
- Supply fan and chiller energy consumption for 'Actual Case' was only about 25 % and 7 % of that in the 'Conventional Case.' The reason for it was cooling is provided by mainly chilled water which reduces the air flow requirement, so decrease the fan energy as well as chiller energy.
- The electricity consumption for pump was higher for 'Actual Case' because of increased water flow rate, but the increase was only about 13.5% of the total energy saving.

It is evident that radiant cooling coupled with FCU results in energy saving of 22%. However in this case study it was found that even though radiant cooling system improves the energy saving, care should be taken to control the condensation problem which is one of the major limitations with radiant cooling systems.

Energy consumption comparison between 'Actual Case' and 'Advance Case'

This section contains the result of recommended system comparing with the actual system in terms of energy saving. The difference of total unmet hours between these two systems is 6.

The total energy saving of Advance Case as compared to the Actual Case is 15%. This energy saving is achieved through reduced cooling load because of using heat recovery and reduced air flow rate. However using heat recovery there is increase in



fan power and motor power to run the wheel. But this penalty is covered by using low air flow rate which is sufficient to maintain the ventilation requirement.

Figure 11- Energy consumption comparison between actual and advance case

Thermal Analysis

With the validated CFD model the simulation of building for both the scenarios has been done to ascertain spatial distribution of indoor air temperature at variable room height and the mean Air temperature of zone for a day in both the alternatives.

Spatial Distribution

The radiant cooling system with the availability of both roof and floor versions results in uniform spatial indoor air temperature with variation in height as shown in Fig 12. In comparison, the conventional case has non uniform temperature variation. This is mainly due to installations of FCU's at a certain elevation in conditioned area.

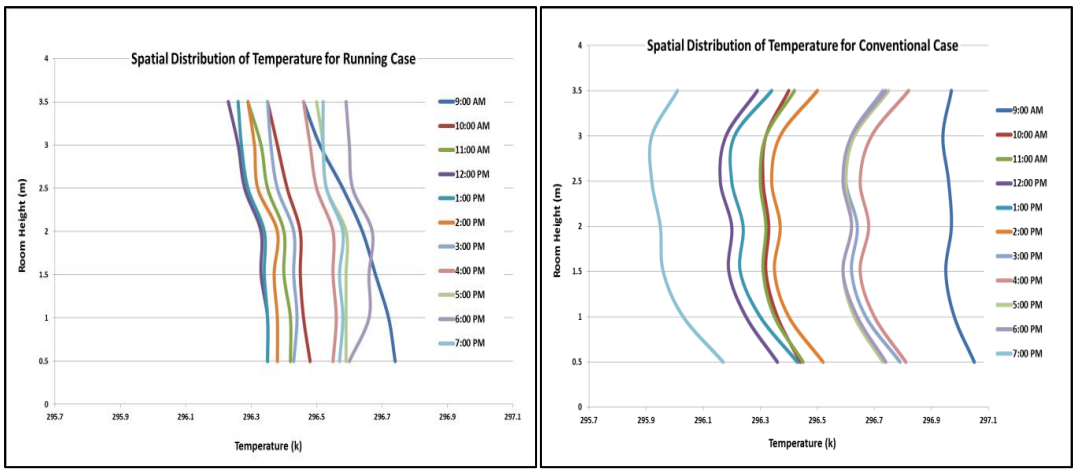


Figure 12- Spatial temperature Variance Actual Case & Conventional Case

Mean Air Temperature

The mean air temperature range for both the scenario has been computed by averaging the temperatures of zone at different incremental times. The actual case, as shown in Fig.13, has higher mean air temperature percentage, lesser fluctuation in the mean air temperatures, which is an important factor for better thermal comfort condition.

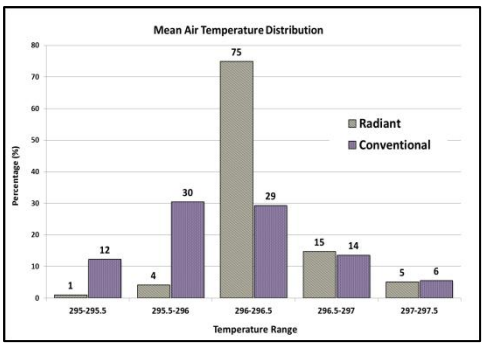


Figure 13- Average air temperature distribution

CONCLUSIONS AND IMPLICATIONS

The radiant cooling system has inherent energy saving design features which results in its improved energy performance over the conventional space conditioning systems. The study was carried out at IT office building at Tech Mahindra, Hyderabad. The parametric analysis done using CFD & EnergyPlus and validation carried out with the actual performance data for a period of three months demonstrates that there is 22% energy saving with running cooling system over simulated conventional central cooling system in composite climate of Hyderabad.

The fan energy consumption is lower by 75 % and due to high chilled water temperature in radiant cooling system the COP of Chiller is higher which results in less electricity consumption for transfer of same or even more thermal energy.

Radiant cooling system maintains uniform and stable indoor air temperature in the zone. Thus better thermal performance is achieved with radiant cooling system while consuming less energy than conventional cooling system.

However in this case study it was found that even though radiant cooling system improves the energy saving, care should be taken to control the condensation problem which is one of the major limitations with radiant cooling systems.

To overcome the condensation problem, an advance case has been simulated by applying DOAS system to handle the latent load of the system and it was found that in additional to overcoming the condensation issue; 15% more energy savings can be achieved over the actual running system.

Further research should be considered for possible use of low heat rejection sources like evaporative cooling, ground source heat pump and cooling tower with heat exchanger etc.

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