Energy and Buildings 97 (2015) 118–128

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Performance evaluation of radiant cooling system integrated with air system under different operational strategies☆

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ARTICLE INFO

Article history:
Received 3 October 2014
Received in revised form 25 February 2015
Accepted 17 March 2015
Available online 26 March 2015

Keywords:
Radiant cooling system
Building energy simulation
Energy saving
EnergyPlus
HVAC
CFD

ABSTRACT

The paper describes a study developed to estimate the energy savings potential of a radiant cooling system installed in a commercial building in India. To evaluate thermal performance and energy consumption, simulations were carried out using FLUENT and EnergyPlus software, respectively. The building model was calibrated using the measured data for the installed radiant system. Then this calibrated model was used to simulate the energy consumption of a building using a conventional all-air system to determine the proportional energy savings. For proper handling of the latent load, a Dedicated Outside Air System (DOAS) was used as an alternative to Fan Coil Unit (FCU) that was installed in conjunction with the radiant cooling system. A comparison of energy consumption calculated that the radiant system was 17.5% more efficient than a conventional all-air system and that a 30% savings was achieved by using a DOAS system compared with a conventional system. The Computational Fluid Dynamics (CFD) simulation showed that a radiant system offers more uniform temperatures, as well as a better mean air temperature range, than a conventional system. To further enhance the energy savings in the radiant system, different operational strategies were analyzed based on thermal analysis using EnergyPlus.

1. Introduction

There is a growing interest in radiant cooling systems as an energy-efficient approach for building space conditioning. Radiant cooling systems are considered a viable innovative approach. In recent years, much research has been conducted on the energy consumption of radiant systems, and it has been found that a radiant cooling system can reduce electrical energy consumption by approximately 40% compared with conventional Heating, Ventilation, and Air Conditioning (HVAC) systems [1,2].

In India, conventional all-air systems typically consume 32–55% of the energy used in a building, depending on the building type and operating hours [3]. A significant part of electric energy is consumed by the fan which is used to transport the cool air as heat transfer medium in the conditioned space. In radiant cooling system temperature of the structure is reduced by supplying chilled water at higher temperature flowing through the pipes embedded in the structure. This increases the radiant heat transfer from the human body and that heat is taken away by the flowing chilled water temperature. The radiant cooling system removes the major part of the sensible load while latent load and remaining sensible load is removed by the ventilation system. Therefore, the radiant cooling system separates the thermal conditioning and ventilation task which results in the significant reduction in the HVAC energy consumption [4–6]. In addition, an integrated radiant cooling system treats the cooling load individually and more uniformly and thus improves thermal comfort [7].

Henze et al. [8] analyzed buildings with Thermo Active Building Systems (One of the type of radiant cooling system). The analysis showed better thermal comfort with low energy consumption, about 20% less, when compared to all-air VAV system. Stetiu [9] describes the parametric study for radiant cooling system in commercial buildings for different location of United States of America through numerical modeling. The results show that the radiant

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http://dx.doi.org/10.1016/j.enbuild.2015.03.030
0378-7788/

cooling system can save on average 30% of the energy consumption and 27% of the peak power demand over a traditional all-air system. Oxizidis and Papadopoulos [10] compared radiant and convective systems with respect to energy consumption and thermal comfort in a test cell representing an office room by carrying out computer simulations of a single office in warm and humid climates. that the simulation study showed that the FCU is consuming more than 14% more primary cooling energy with respect to the radiant systems. Niu et al. [11] evaluated the system performance and energy saving potential of a radiant cooling system with desiccant cooling through energy simulation and result indicated that chilled ceiling combined with desiccant cooling could save up to 44% of the primary energy consumption, in comparison with conventional constant volume all-air system. Sodec [12] compared the energy cost of a VAV and a cooling ceiling system using a numerical simulation program TRNSYS. From a specific cooling load of 45 to 55 W/m^2, the first costs of the cooling ceiling system can be well below those for the VAV system up to 20%.

The studies cited above demonstrate that the radiant cooling systems have a potential to save signification energy as compared to the conventional all air systems. However, the performance of the radiant cooling system is depend on the climatic condition; like the use of radiant cooling system in hot and humid climate is very critical because of condensation problem [13,14]. A simulation-based study demonstrated that a radiant slab system provided 10 to 40% better energy performance than a conventional system, depending on the climate type. The best performance was achieved in dry climates [15].

The radiant cooling system in itself, because of its design limitations, does not address the latent load of the conditioned area; as a result, condensation may occur on the cooling surface, depending on the prevailing environmental conditions. However, add-on supplemental systems can be deployed to overcome this disadvantage [16]. To prevent condensation, additional dew point temperature control of the conditioned space using a parallel ventilation system is needed to maintain indoor air quality [17].

Previous studies show that many simulation studies have been performed globally for radiant system technology. In India, radiant systems are not fully understood because they do not cater the latent heat demand. The design of a radiant system is complicated because of the coupling between thermal load, building structure, and hydronic system and its impact on thermal comfort [18–20]. Even experienced professionals acknowledge the complications in radiant system design and integration. This study describes the integration of a radiant system with other technologies to cater the latent load. The calibrated simulation model approach is used in this paper to analyze the performance of radiant cooling system alongwith the integration of technologies to provide the latent loads and outside air.

Building energy simulation tool model the energy performance of the building, but well mixed air approximation is limitation of this type of modeling because air temperature is not uniform throughout any specific location in the space. The non-uniform temperature distribution could increase the thermal discomfort of the occupants. CFD simulation can provide detailed thermal environment and contaminant information. In recent years, CFD has become a more reliable tool for the evaluation of indoor thermal comfort and air quality. However, the application of CFD to real building design has been limited as it requires excessive computer resources and long running time. [21]. However, complex and less common systems such as radiant cooling systems could benefit from the detailed CFD simulations in order to gain the confidence in the ability of these system in providing better thermal comfort. This paper demonstrates the use of CFD modeling to analyze the radiant cooling system for thermal comfort analysis.

2. Evaluation approach

The main objectives of this paper are to (1) evaluate the energy savings achieved by a radiant cooling system installed in an existing IT company building compared with a conventional all-air HVAC system and (2) use simulation to study possible enhancements of its performance, from both the energy and thermal environment perspectives. To meet these objectives, building models were developed in EnergyPlus and ANSYS FLUENT software, respectively. Three energy models of the buildings were developed in EnergyPlus. The building energy models in this paper are referred as follows:

- the existing radiant system—"Running Case,"
- the hypothetical conventional HVAC system—"Conventional Case," and
- the radiant system with additional energy-saving options—" Advanced Case."

The Running Case represents the existing radiant system in the building, which is coupled to FCUs to cater the latent heat load. This model, calibrated with the measured data, was simulated for energy performance. Then the same cooling load was applied for the Conventional Case, which represents an auto-sized conventional central cooling system. The objective of the calibration was to apply identical cooling loads on the Conventional Case and the Running Case to make a reasonable comparison. To enhance the energy savings in the existing building, the Running Case was modified by replacing the FCUs with a DOAS coupled with an Energy Recovery Wheel (ERW). In this Advanced Case, deficiencies in the radiant cooling system were eliminated. To further improve energy efficiency, different operational strategies were analyzed based on thermal analysis. The whole methodology is shown in Fig. 1.

Computational Fluid Dynamics (CFD) tools were used to capture spatial and temporal variations in the flow and thermal properties for specified boundary condition. To evaluate indoor air quality and thermal comfort, CFD simulations were conducted for the Running Case and the Conventional Case. The CFD model was validated with the energy model of the building. The energy analysis was done using the EnergyPlus v8.0 [22] program, and thermal performance was evaluated using the CFD software ANSYS FLUENT v14.5 [23], which can effectively model and analyze heat transfer applications. Thermal modelling of HVAC system was performed using EnergyPlus and the CFD modeling was used for simulating the effect of air and temperature distribution. For the CFD analysis, the boundary conditions were collected from EnergyPlus simulated data with taking hourly radiant floor and ceiling temperature constant as an assumption.

3. Building modeling

This section discusses the methodology followed to develop the three cases for simulation and explains the input parameters required for modeling.

3.1. Development of the running case model

3.1.1. Building description

The modeled building is an IT office building of the company Tech Mahindra located in Hyderabad, India, in a composite climatic zone [24]. It has a conditioned space of approximately 354 m^2. Fig. 2 shows a schematic of the building geometry and HVAC system configuration. There are two chillers for the production of cold water. One chiller, with a capacity of 12 TR (tones of refrigeration) was installed for the radiant cooling system. The other is a large,