Building and Environment 145 (2018) 196–212

Contents lists available at ScienceDirect

Building and Environment

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

Evaluation of thermal comfort criteria of an active chilled beam system in tropical climate: A comparative study

Abdus Salam Azad[a,b], Dibakar Rakshit[b], Man Pun Wan[c,*], Sushanth Babu[a], Jatin N. Sarvaiya[a], D.E.V.S. Kiran Kumar[a], Zhe Zhang[a], Adrian S. Lamano[a], Krithika Krishnasayee[a], Chun Ping Gao[d], Selvam Valliappan[d], Alice Goh[d], Alvin Seoh[d]

[a] Energy Research Institute at NTU (ERI@N), Nanyang Technological University, 637553, Singapore
[b] Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi, 110016, India
[c] School of Mechanical & Aerospace Engineering, Nanyang Technological University, 639798, Singapore
[d] Built Environment Research and Innovation Institute (BERII), Building and Construction Authority (BCA), Singapore

A R T I C L E I N F O

Keywords:
Active chilled beam
Conventional fan coil unit
PMV-PPD model
Radiant asymmetry
Thermal comfort
Vertical air temperature difference

A B S T R A C T

Air-conditioning systems are employed to provide thermal comfort inside buildings. Therefore, several air-conditioning and mechanical ventilation (ACMV) systems have been tested and applied in different climates. Chilled beam systems are a new addition to it and have been in the application in Europe and North America since last two decades. In the present study, comparative performance of active chilled beam (ACB) system with conventional fan coil unit (FCU) system has been appraised in regards to thermal comfort for the tropical region of Singapore. Experiments were carried out in a simulated office building with approximately 80% glazed area under real environmental conditions. Room air temperature, air velocity, mean radiant temperature (MRT) and relative humidity which are important thermal comfort parameters were measured in perimeter zone inside the cells and assessed. It was perceived that the ACB system was providing acceptable thermal comfort as per the standard of SS 554. General thermal comfort has been assessed based on an index of PMV-PPD model and graphical method. With regard to the local thermal discomfort: indices of air draught, vertical air temperature difference (VATD) and radiant temperature asymmetry have also been evaluated. The entrance of solar radiation through window façade may have a significant impact on the asymmetry of the radiant field and can enhance thermal discomfort of the occupants. Therefore, in the study radiant temperature asymmetry has been calculated extensively. The results show that ACB system yields satisfactory thermal environment as per ISO 7730 standard and sometimes performs even better than conventional FCU system.

1. Introduction

Air-conditioning and mechanical ventilation (ACMV) systems uphold a comfortable and healthy environment inside buildings. A recent addition to the several ACMV systems available in the market, chilled beam technology is gaining popularity due to its positive outcomes concerning energy conservation, thermal comfort and reduced cost. Since the last two decades, chilled beams are widely used in Europe and North America [1–3].

An Active Chilled Beam (ACB) receives pre-treated (primary) air through the air handling unit (AHU) and chilled water (CHW) flow into the cooling coil within the terminal unit mounted on the ceiling. The schematic of an ACB terminal unit is represented in Fig. 1 to understand its working principle. The primary air is injected through a series of nozzles within the beam to condition the room air. Because of low local static pressure region created near the nozzle outlet, the room air rises upwards. The secondary (induced) air takes away the sensible load of the conditioned zone while passing over the cooling coils. It then mixes with the primary air in the mixing chamber, and this mixed air then discharges back through the slots to the zone. The ACB terminal units mounted on the ceiling maintain a sufficient discharge velocity to ensure a well-mixed room air distribution. The primary air is responsible

---

* Corresponding author.
E-mail addresses: esz148318@iitd.ac.in (A.S. Azad), dibakar@iitd.ac.in (D. Rakshit), mpwan@ntu.edu.sg (M.P. Wan), sushanth@ntu.edu.sg (S. Babu), Jatin@ntu.edu.sg (J.N. Sarvaiya), kirankumar.devs@ntu.edu.sg (D.E.V.S.K. Kumar), zhe.zhang@ntu.edu.sg (Z. Zhang), adrianlamano@ntu.edu.sg (A.S. Lamano), kkrithika@ntu.edu.sg (K. Krishnasayee), GAO_Chun_Ping@bca.gov.sg (C.P. Gao), Selvam_Valliappan@bca.gov.sg (S. Valliappan), Alice_GOH@bca.gov.sg (A. Goh), alvin_seoh@bca.gov.sg (A. Seoh).

https://doi.org/10.1016/j.buildenv.2018.09.025
Received 26 June 2018; Received in revised form 14 September 2018; Accepted 15 September 2018

for the removal of the latent heat load.

In literature, the authors have validated the performance of the ACB system [4,5]. Filipsson et al. [6] developed a numerical model of the ACB system to compute its cooling capacities. The model distinctly includes the effect of buoyant forces acting on the cooling coil in the beam. The model was calibrated with measured data and showed good agreement in a broad range of working conditions.

In terms of energy-savings, ACB systems can achieve savings of up to 20–30% related to traditional air conditioning systems, depending upon different locations [7–9]. Betz et al. [10] reported the issues emerging while modeling the ACB system using various simulation tools. It was asserted that factors like induction ratio, manifold chilled water loops, humidity regulation and ACMV system configurations should be taken into consideration while doing simulations to attain accurate results. It was suggested by Stein and Taylor [11] that the ACB system designed for low supply air discharge rate along with intermediate CHW temperature, results in improvement in its energy performance compared to variable airflow with reheat systems. Authors also argued that the ACB system performs well under high sensible load.

Kosonen and Tan [12] conducted an experimental study to explore the usefulness of the ACB system in hot and humid climate. It was shown that condensation in the beam system could be prevented when infiltration is low, and supply air discharge is ample to remove humidity caused by occupants. Loudermilk and Alexander [13] suggested that chilled beams can be better alternatives compared to air-water distribution systems when it comes to humidity controls. It was also concluded that humidity and condensation risk could be overcome using chilled beams in a humid climate.

Invariable temperature, ample rainfall and high humidity all over the year are the main characteristics of tropical climate [14]. In Singapore, which is located near the equator, the diurnal limit of temperature lies between 25 °C and 33 °C. The diurnal range of relative humidity (RH) range is around 60% in the middle of the afternoon and could be as high as 90% in the early morning. The typical dew point temperature is near 24 °C, and the absolute humidity is 19.5 g/kg in the daytime and 18.5 g/kg in nights all over the year [12,15]. Cooling and dehumidification is a challenge in the tropical climate. For this reason, it is essential to maintain the RH together with room temperature.

In the view of thermal comfort, it has been reported that similar or better thermal environment can be produced by the ACB system, related to the other conventional air-conditioning systems [7]. Authors have assessed general thermal comfort in perspective of comfort indicator like predicted mean vote (PMV) and; it has been found that it can assure satisfactory thermal environment. However, in addition to general thermal comfort, it is also essential to assess local thermal discomfort, in terms of air draught, vertical air temperature difference (VATD), etc. [16,17].

Zboril et al. [18] conducted an experimental study in a test-bed facility consisting of multiple chilled beams under induced airflow rates and varied heat loads and investigated the draught rate and VATD. The result indicated that the draught rate was below 20% and VATD was below 3 °C for all test conditions, which conforms to the thermal comfort criteria. Koskela et al. [19,20] carried out an experimental study with test-bed facility exposed in a real environment and multiple numbers of ACBs. In the study, tests were carried out with varied cooling loads replicating summer, spring/autumn and winter conditions, and for which airflow patterns and mean airspeeds were investigated. The results showed that the internal cooling loads could impact the airflow patterns and draught possibilities.

In order to investigate the consistency of the thermal environment produced by the ACB system, a test-bed facility was developed by Rhee et al. [21]. A comparative study was made between traditional air-conditioning systems and the ACB system. The performance indices of air diffusion parameter index (ADPI), air velocity, and VATD were adopted in order to study the consistency in thermal environment of the ACB system. The results indicated that uniform thermal environment could be produced by the ACB system with low air discharge rate through AHU compared to traditional systems.

The present study has been carried out in the tropical region of Singapore. The objective of this study is to evaluate thermal comfort characteristics of the ACB system and compare it with a conventional FCU system. Experiments have been conducted using a test-bed facility, representative of an office building with about 80% glazed area, exposed to real outdoor conditions. In order to assess general thermal comfort, indices of predicted mean vote – people percentage dissatisfied (PMV-PPD) and graphical method have been used. The indices of air draught, VATD along with radiant temperature asymmetry have been adopted to evaluate local thermal comfort. The impact of solar radiation on radiant temperature asymmetry has also been assessed extensively to study their influences on indoor thermal comfort.

2. Experimental set-up

In order to assess the thermal comfort criteria of ACB system compared with the conventional FCU system, each of these systems was installed in two cells of the test-bed of BCA SkyLab, Singapore. Conventional FCU and ACB system were employed in the reference and test cell, respectively. The schematic of the test-bed facility is presented in Fig. 2. Both cells are a replica of each other, and their dimensions are 8.41 m (L) × 5.54 m (W) × 3.47 m (H) up to the ceiling. The orientation of the cells can be changed as the test-bed facility is constructed over a rotating platform.

The supply and return air schematic of the conventional FCU and ACB systems are depicted in Figs. 3 and 4, respectively. The conventional FCU system employed an AC-motor FCU to provide air-conditioning in

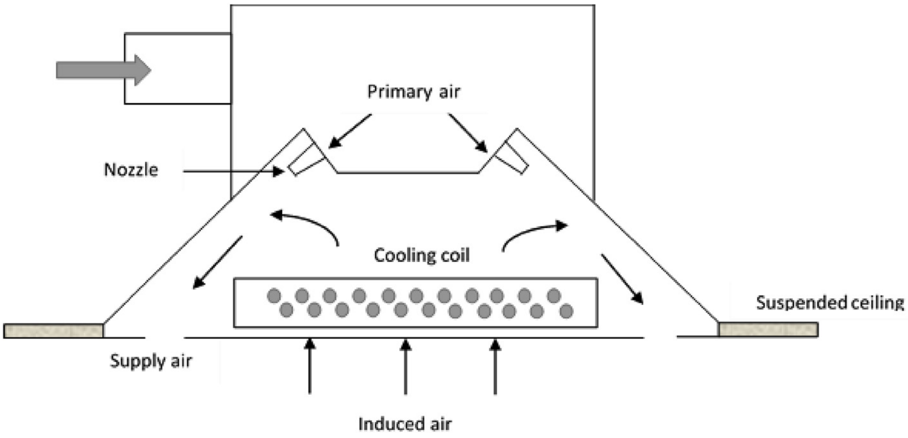

Fig. 1. Schematic diagram of an ACB terminal unit.