Energy and Buildings 158 (2018) 1736–1750

Contents lists available at ScienceDirect

Energy and Buildings

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

Experimental investigation and data-driven regression models for performance characterization of single and multiple passive chilled beam systems

Janghyun Kim [a,b], Athanasios Tzempelikos [b,c,*], W.Travis Horton [b,c], James E. Braun [a,b,c]

[a] School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA
[b] Center for High Performance Buildings, Ray W. Herrick Laboratories, Purdue University, 140 S. Martin Jischke Dr., West Lafayette, IN 47907, USA
[c] Lyles School of Civil Engineering, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 7 June 2017
Received in revised form 9 November 2017
Accepted 3 December 2017
Available online 5 December 2017

Keywords:
Passive chilled beams
Data-driven regression models
Cooling capacity
Chilled surface temperature

ABSTRACT

The performance of passive chilled beams is characterized in this study to understand their physical behavior when applied in real indoor environments. Two full-scale experimental studies were conducted to map the performance of passive chilled beams in two different experimental settings: (i) single passive chilled beam testing in a controlled laboratory environment and (ii) multiple passive chilled beams testing in a real open plan office setting. The experimental results were then used to develop regression models for predicting the total cooling capacity and chilled surface temperature of single and multiple passive chilled beams, as a function of water flow rate, water supply temperature, air temperature above the chilled beam and area-weighted uncooled surface temperature in the space. The developed models showed good agreement with experimental results and can be used in building energy modeling tools for system simulation using passive chilled beams. Finally, it was found that the conventional method of predicting the total cooling capacity of a passive chilled beam from individual beam laboratory tests or manufacturers' catalogs may significantly underestimate the system performance in multi-unit configurations. These differences could influence optimal system sizing and commissioning and should be considered in future studies.

1. Introduction

Reducing energy consumption in buildings is an important part of reducing global energy usage and environmental impact. The global energy demand in buildings will approximately double by 2050 according to the International Energy Agency due to the "rising number of residential and commercial buildings" [1]. While more than two-thirds of existing buildings are expected to remain until 2050, significantly reducing energy use in the building sector requires retrofitting existing buildings with advanced technologies. Furthermore, modeling of these technologies is a critical part of assessing their energy and economic potentials towards realizing success in the marketplace.

Passive ceiling cooling systems are one of the promising technologies among other space cooling systems in buildings. The passive ceiling cooling systems handle most of the sensible cooling load by a combination of radiation and natural convection from the ceiling level in a space, while the latent load is handled separately using a parallel ventilation system. Due to the nature of radiation and natural convection, depending on space characteristics and specific conditions, accurate modeling of these systems is not an easy task. A thorough overview of modeling approaches for passive ceiling cooling systems [2] showed the complexity of the problem depending on the specific system configuration and different modeling applications. Although ceiling panel types [3–22] and embedded types [23–32] of ceiling cooling systems have been studied extensively, there is a lack of related studies specifically on passive chilled beams.

Passive chilled beams typically use typical fin-tube heat exchangers and a horizontal perforated panel at the bottom to increase both radiative and convective heat transfer. Although they are a promising technology, modeling their performance is challenging because (i) they can have a complex geometry and (ii) the primary heat transfer mechanisms of radiation and natural convection are strongly coupled to the space characteristics and thermal conditions. Thus, it is important to properly character-

* Corresponding author at: Lyles School of Civil Engineering, Purdue University, 550 Stadium Mall Dr West Lafayette, IN 47907, USA.
E-mail address: ttzempel@purdue.edu (A. Tzempelikos).

https://doi.org/10.1016/j.enbuild.2017.12.003
0378-7788/

Nomenclature

A	Area, m^2
AUST	Area-weighted uncooled surface temperature, °C
c	Specific heat, J/kg-K
D	Diameter, m
$\dot{m}$	Mass flow rate, kg/s
num	Number counts
PCB	Passive chilled beam
$\dot{Q}$	Heat extraction rate or cooling capacity, W
$\dot{Q}$	Volumetric flow rate, CFM
T	Temperature, °C
v	Velocity, m/s
r	Correlation coefficient

Greek Symbols

γ	Weighting factor
ε	Emissivity
μ	Uncertainty

Superscript

'	Per unit length

Subscript

0	Nominal
air	Air
avg	Average
cap	Cooling capacity
E	East
flr	Floor
ind	Indoor (air)
N	North
PCB	Passive chilled beam
PCC	Pearson's correlation coefficient
r	Return
S	South
s	Supply
surf	Surface
top	Top
tot	Total
wat	Water
W	West

ize the performance of passive chilled beams in order to assess their potential compared to conventional cooling systems. Modeling passive chilled beam performance can be focused on different aspects of the system depending on the objectives and application. The heat transfer rate characteristics under different operating conditions can be studied to estimate the energy performance of the system. The developed air flow pattern, driven by natural convection, or combined with forced convection (parallel air system for ventilation) can be investigated to predict the flow and temperature field around occupants at the breathing level, for detailed thermal comfort evaluation. The noise and vibration levels of the passive chilled beam under various operating conditions are also of interest for the indoor environment. This study focuses on characterizing the energy performance of passive chilled beams.

There are various passive chilled beam manufacturers [33–42] and some of them provide publically available cooling capacity performance maps. These performance maps are mostly used for principal sizing, but do not include detailed performance data under various operating conditions. The few published studies on experimental investigation of passive chilled beams [43–46] mostly focus on natural convection and the air flow pattern at the breathing level. For example, different opening ratios of the false ceiling and the location and strength of the thermal gain at the breathing level below the passive chilled beam have been studied. Although these performance maps and experimental investigations provide useful findings related to the behavior of passive chilled beams, it is also important to model and understand the overall performance and potential of passive chilled beams when installed within buildings.

There are several studies and standards related to component and system-level modeling of passive chilled beam model. The latest standard for testing chilled beams includes a data-driven modeling approach for both active and passive chilled beam types [47,48]. The regression model in this standard can predict total cooling capacity for different values of water mean temperature, water flow rate and elevation of the location. While this model is very useful for characterizing total cooling capacity of a passive chilled beam, several improvements can be made. For example, the model does not predict separate convection and radiation cooling characteristics of passive chilled beams which would be needed when integrating the model in a system simulation. Also, this model requires an iterative solution approach for determining the mean water temperature at each time step – a computationally expensive process when implemented in a building energy simulation tool. In addition, it is not clear how well a model developed from test data obtained from a single chilled beam in a laboratory environment would predict performance for multiple chilled beams installed in a building.

This paper attempts to improve on the data-driven modeling approach presented in the test standard and evaluates the accuracy of a model determined for an individual passive chilled beam in a laboratory setting when utilized for a building installation with multiple chilled beams. In order to carry out this work, two full-scale experimental studies were performed: (i) single passive chilled beam testing in a controlled laboratory environment and (ii) multiple passive chilled beam testing in real open plan office setting. The experimental results were then used to develop semi-empirical regression models for predicting the total cooling capacity and chilled surface temperature of the passive chilled beams. The developed models do not require iterative calculations, can be used in building energy modeling tools for system simulation using passive chilled beams, and provide information for quantifying convection and radiation cooling of passive chilled beams. Differences between performance for the laboratory and office chilled beams are presented and discussed.

2. Performance measurements of passive chilled beams

Two different experiments were conducted to enable performance characterization of passive chilled beams. The primary goal was to develop and compare performance models based on the experimental results from (i) testing a single passive chilled beam in a controlled environment and (ii) testing multiple passive chilled beams in a real office setting.

2.1. Performance measurements of a single passive chilled beam in a controlled environment

The purpose of this experiment was to generate performance data for characterizing the performance of a single passive chilled beam under controlled conditions and to develop performance models that can be used in system simulation tools. Under different operating conditions (air temperature, surface temperatures, water supply temperature and water flow rate), comprehensive parameters were measured to capture both convection and radiation characteristics of the passive chilled beam.