Energy and Buildings 82 (2014) 482–491

Contents lists available at ScienceDirect

Energy and Buildings

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

Sensitivity analysis of the thermal performance of radiant and convective terminals for cooling buildings

J. Le Dréau, P. Heiselberg

Department of Civil Engineering, Aalborg University, Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark

ARTICLE INFO

Article history:
Received 22 September 2013
Received in revised form 27 April 2014
Accepted 1 July 2014
Available online 9 July 2014

Keywords:
Floor cooling
Cooled wall
Cooled ceiling
Active chilled beam
Emitters
Sensitivity analysis
Cooling need
Convective heat transfer coefficient
Air temperature stratification
Comfort

ABSTRACT

Heating and cooling terminals can be classified in two main categories: convective terminals (e.g. active chilled beam, air conditioning) and radiant terminals. The mode of heat transfer of the two emitters is different: the first one is mainly based on convection, whereas the second one is based on both radiation and convection. In order to characterise the advantages and drawbacks of the different terminals, steady-state simulations of a typical office room have been performed using four types of terminals (active chilled beam, radiant floor, wall and ceiling). A sensitivity analysis has been conducted to determine the parameters influencing their thermal performance the most. The air change rate, the outdoor temperature and the air temperature stratification have the largest effect on the cooling need (maintaining a constant operative temperature). For air change rates higher than 0.5 ACH, differences between terminals can be observed. Due to their higher dependency on the air change rate and outdoor temperature, convective terminals are generally less energy effective than radiant terminals. The global comfort level achieved by the different systems is always within the recommended range, but differences have been observed in the uniformity of comfort.

1. Introduction

Differences can be observed between offices built nowadays and the ones built in the eighties or before. First of all, the level of insulation and air tightness of buildings has increased due to strengthening of the different building regulations. A better treatment of daylight by architects and the development of new products have led to an increase of the glazed area of buildings; fully glazed façades are becoming more widely installed. The use of buildings has also changed with the emergence of computers and other electronic devices, thus increasing internal heat loads. For these reasons and also due to a raised focus on thermal comfort, more cooling systems are installed in offices. In the European Union, the cooled area in non-residential buildings has increased by 45% between 2000 and 2010, resulting in an electricity consumption of 95 TWh for the EU-15 members [2]. This situation creates serious supply difficulties during peak load periods, especially in southern European countries such as Spain or Italy [3].

Convective terminals are the most widely installed cooling system, despite their high initial costs, high energy use and often unacceptable indoor climate. Occupants sometimes complain about the noise or the draught of this type of system [4]. Switzerland and the state of Hamburg in Germany have even restricted the installation of full air conditioning systems for buildings [5].

Radiant technology is an alternative to air-based emitters. Contrary to convective terminals, which transfer heat mainly by convection, radiant terminals transfer heat partly by radiation to (or from) the neighbouring surfaces, and partly by convection to (or from) the indoor air [6]. The first radiant cooling system was installed after the First World War, in the Bank of England [7]. In the 1990s, European offices were increasingly equipped with cooled radiant ceilings because of longer overheated periods during summer time [8]. In 2004, a cooled radiant floor was installed in the humid climate of Bangkok airport [9]. More recently, radiant walls have been introduced to the market.

Most of the studies comparing radiant and air-based systems conclude to the lower energy use of radiant systems [10–16]. Radiant systems are an efficient way of transporting energy [4], mainly due to the higher heat capacity of water and the reduced fan usage. Moreover, the large surface of exchange of radiant systems allows the use of source temperature closer to the room temperature, increasing the efficiency of production systems. The total energy savings oscillate between 10 up to 60%, depending on the climate, the source considered, the area of the radiant system and the efficiency of the different components. Fabrizio et al. [16] have

E-mail addresses: jld@civil.aau.dk (J. Le Dréau), ph@civil.aau.dk (P. Heiselberg).

http://dx.doi.org/10.1016/j.enbuild.2014.07.002
0378-7788/

Nomenclature

A	surface area (m^2)
ACR	air change rate (ACH)
D_h	hydraulic diameter (m)
C_p	heat capacity (J/kg K)
F_{p-i}	view factors from the plane to the surface i (calculated according to [1])
g	total solar energy transmittance
H	height of the surface (m)
h	convective heat transfer coefficient (W/m^2 K)
Q	heat flow (W)
q	heat flux (W/m^2)
R	thermal resistance (m^2 K/W), surface resistances not included
RR_{CB}	recirculation rate, only applicable for the active chilled beam (h^{-1})
T	temperature (°C)
ΔT_{i-j}	temperature difference $T_i - T_j$ (K)
V	volume (m^3)

Greek symbols

ρ	density (kg/m^3)
μ	mean cooling need (W/m^2)
σ	standard deviation of the cooling need (W/m^2)

Subscripts

cond	conduction
conv	convection
pr	plane radiant
rad	radiant
rad LW	long-wave radiation
rad SW	short-wave radiation
i	surface i

compared numerically the performance of radiant floor and ceiling systems versus all-air and fan coil systems. Dynamic simulations of a typical office building showed that the cooling energy use is greatly reduced for warm climates, whereas the reduction is smaller for cold climates.

In addition to the total energy use, some studies compare the energy need in the space. Differences in the heat balance are noted in several publications [11,15–20], but the effect on the cooling need is not clearly defined: some studies show a higher demand [17] for radiant terminals, whereas some others conclude to a lower [18,19] or similar demand [11,16]. As stated by Djunaedy et al. [20] and Feng et al. [17], “no research can be found that fundamentally studies the differences of the heat transfer process in zones conditioned by an air and a radiant system”. In most of the studies, the dynamic simulations do not highlight the sensitivity of one specific parameter on the cooling need. Parameter variation is needed to emphasize the influencing factors.

In this paper, four terminals have been selected (active chilled beam, radiant floor, radiant wall and radiant ceiling) and their thermal performances have been compared. This paper focuses on describing the heat transfer within the space. Therefore, the source and the type of energy used to remove heat have not been taken into consideration. Humidity control has also not been considered, as the problem of humidification or dehumidification has to be treated in the plant, before the air enters the space. The main objective is to identify the case(s) in which the different technologies achieve the best performance in maintaining a constant operative temperature of 26 °C. The robustness of the different cooling systems will be evaluated by performing sensitivity analyses and

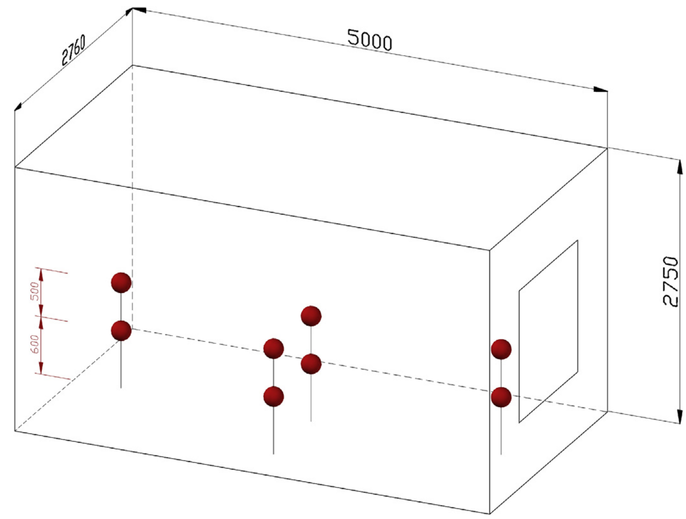

Fig. 1. Geometry of the room (dimension in mm). Red dots indicate the different positions considered for the occupant. (For interpretation of the color information in this figure legend, the reader is referred to the web version of the article.)

parameter variations. The parameters varied are related to the outdoor conditions (outdoor temperature, part of direct to total solar radiation), the type of ventilation system (air change rate, air temperature gradient, convective flow in the room), the room properties (emissivity and absorptivity of the internal surfaces) and the position of the person/sensor in the room. A typical European office building has been chosen as the base case and numerical simulations have been performed under steady-state conditions.

2. Case study

2.1. General parameters

The case of an office room located in Europe has been chosen to study the influence of the type of terminal on the cooling need (Fig. 1). The internal dimensions of the room have been chosen similar to the PASSYS test cell: 5 × 2.76 × 2.75 m (length × width × height), resulting in a floor area of 13.8 m^2 [21]. A window facing south is providing daylight to the room (g-value of 0.6). The thermal characteristics of the building components are given in Table 1. The insulation level of the floor and the roof is relatively high, in order to model the case of a multi-storey building. Internal heat loads are equal to 20 W/m^2 [22]. The outdoor conditions have been selected from the weather data of the Design Reference Year (DRY) in Copenhagen, Denmark. It corresponds to a hot summer day (Table 2). The total heat load in the room (internal and solar) is equal to around 40 W/m^2.

Table 1
Thermal properties of the construction elements.

Surface	R (m^2 K/W)
Walls	6.66
Window	0.71
Floor	10.00
Roof	10.00

Table 2
Definition of the base parameters (13th of July, 3 pm).

$q_{solar\ normal,\ horizontal}$ (W/m^2)	296
$q_{solar\ diffuse,\ horizontal}$ (W/m^2)	389
Solar azimuth (°)	234
Solar height angle (°)	47