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Experimental study of diffuse ceiling ventilation coupled with a thermally activated building construction in an office room

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ABSTRACT

This paper presents and analyses the performance of an integrated system with diffuse ceiling ventilation and a thermally activated building construction. A full-scale experiment is carried out in a hot box with an office setup. The performance of the integrated system is evaluated under different boundary conditions, considering different weather conditions, internal heat loads, TABS activation modes and with/without diffuse ceiling. The measurement results indicate that the diffuse ceiling plays a beneficial role improving thermal comfort in the occupied zone. However, the diffuse ceiling has the opposite effect on energy performance when TABS is activated in heating or cooling mode. Finally, the air temperature distribution in the plenum and the surface temperature distribution of the diffuse ceiling point out that the air does not perfectly mix in the plenum, the air is not evenly distributed throughout the entire ceiling area and the radiation cooling potential of diffuse ceiling is not sufficient. Thus, a further study should be conducted on optimizing diffuse ceiling and plenum design.

1. Introduction

The demand for comfort cooling is dramatically increasing in all European countries. As predicted by EECCAC [1], a four-fold growth of energy consumption for cooling will occur between 1990 and 2020 in EU 15. The reasons for the expansion of cooling demand are manifold. First of all, the constructional and physical boundary conditions of buildings have been changing. For example, the buildings are designed to be more airtight, with better thermal insulation and intensive use of glazed façades. These changes considerably reduce the energy demand on heating, but also lead to an increase on cooling demand. Secondly, the tightened requirements on indoor comfort and the increase of internal loads (IT equipment) contribute to a rise on cooling demand. Finally, the climate change with an increase of outdoor temperature in the summer period exacerbates the situation.

Passive cooling by ventilation is regarded as a promising strategy, which has been proved to have a significant free cooling potential in the moderate or cold climates of Central, Eastern and Northern Europe [2]. For the conventional ventilation solutions, it is necessary to preheat the outdoor air during winter to avoid the draught risk in the occupied zone. This rises the energy use and investment cost. An alternative ventilation concept is known as diffuse ceiling ventilation (DIFCV), where the fresh air is supplied through perforations in suspended ceiling panels [3]. Due to the large opening area, air flow is delivered into the room with very low velocity and with no fixed jet direction, so the name 'diffuse'. This ventilation system has been demonstrated that it has superior performance on handling high heat load by directly supplying low temperature air and without significant draught risk [4,5]. On the other hand, a plenum above suspended ceiling is used to deliver air instead of conventional duct system, thus the pressure drop of the system is largely reduced, making it possible to implement with natural ventilation [5–7]. This ventilation concept is wildly used in the livestock buildings because of its low investment cost and high thermal comfort [8,9]. Recent years, more and more applications and studies have been reported regarding utilization of DIFCV in the indoor space for human being, especially for offices and classrooms with high heat load and high ventilation demands [6,5,10,11].

Natural ventilation as a passive cooling strategy strongly depends on the climatic conditions. When natural ventilation is insufficient to cool down the building or heating is required, thermally activated building system (TABS) could serve as a supplementary system to deal with the excessive cooling or heating

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Nomenclature

A	area [m^2]
ACH	air change rate [1/h]
DR	draught risk [%]
PD	percentage of dissatisfied [%]
PMV	preceded mean vote
C_p	specific heat [J/kg K]
M	flow rate [kg/s]
t	temperature [°C]
Q	heat flow [W]
h	heat transfer coefficient [W/m^2 K]

Subscripts

a	air
avg	average
DIFCV	diffuse ceiling ventilation
down	lower zone
envelop	other envelop
ex	return
façade	façade
in	inlet
op	operative
re	return
s	surface
source	heat source
su	supply
surround	surrounding zone
TABS	thermally activated building construction
up	upper zone
vent	ventilation
w	water

demands. TABS is a type of radiant cooling and heating system, where the water carrying pipes are embedded in the building elements [12]. Because of the high inertia of thermal mass, the peak load will be reduced and some of cooling load will be transferred beyond the time of occupancy. In addition, due to the large heat transfer surface, it is possible to heat or cool effectively, even with very slight temperature differences between the concrete slab and the room. This will result in a high efficiency of energy system and increasing application of renewable energy resource such as ground water, heat pump and solar collectors [13–15]. Therefore, the integrated system has the potential to provide cooling, heating and ventilation for an office building all year around with high thermal comfort and low energy consumption.

The combination of radiation cooling/heating and ventilation systems has been extensively studied. The most common application is cooled ceiling with displacement ventilation. This integrated system has been proved to be more energy efficient than conventional air conditioning systems, since it could work together with night cooling and heat storage facilities [16,17]. However, in order to avoid the risk of draught in the occupied zone, the cooling load should be restricted to below 100 W/m^2, the height from floor to ceiling should be higher than 2.5 m and the cooling outputs of ceilings should also be regulated appropriately [16]. In addition, the downward convective flow produced by cooling panels mix with the upward displacement flow, which gives a more mixed condition than pure displacement [17,18]. The combination of floor cooling with displacement ventilation is also considered possible, although the draught risk at the ankle level and vertical temperature gradient need to be controlled carefully [19]. Since the advantage of displacement flow in respect to the air quality is receded when cooled ceiling is used to remove high cooling load, another solution of cooled ceiling coupled with mixing ventilation were studied. The results indicated that a mixing ventilation system could provide uniform pollutant distribution if the entire ceiling be covered by cooled areas. However, a draught risk was observed if high cooling load was presented, in the same manner as displacement ventilation [20].

The new system solution combining DIFCV and TABS has been proposed recently by Tao Yu et al. [21]. They specified five operation models based on different climatic and occupied conditions. A case study of a typical office using this solution was compared with those with other traditional HVAC system by energy simulation. The results indicated that the new system has a large energy saving potential once it is properly designed and controlled and the ventilation period is extended by using diffuse ceiling supply. This study mainly conducted by theoretical analysis, therefore, the performance of the system should be further evaluated and validated by experimental study. A key issue is the harmony of the combination between these two techniques. Most of studies regarding TABS have pointed out it is necessary to have large surface areas with exposed concrete. However, in this coupled system, the TABS is encapsulated by a suspended ceiling. A reduction on the radiation heat exchange between the TABS and the room surfaces will be expected. On the other hand, distributing the supplied air by a plenum allows direct contact between the air and the thermal mass of the concrete slabs. As a result, the convection heat exchange between TABS and air will vary, depending on the temperature difference and air flow rate. A research of integrated ventilation and night cooling with DIFCV in a classroom was performed by Hviid [22], and the results indicated that the extra free cooling potential made available by activating the thermal mass of the concrete slab in the plenum. Therefore, the impact of suspended ceiling on the thermal performance of TABS should be investigated in the experimental study. Second, in the simulation, the air was predicted to be perfectly mixed in the plenum and evenly distributed through entire ceiling area. Actually, the air condition in the plenum is influenced by the heat exchange between supply air and thermal mass and the mixing level is determined by configuration of plenum and inlet. It is critical to exam the air flow pattern in the plenum and through diffuse ceiling.

The objective of this study is to analyze the performance of the system combining DIFCV and TABS by means of an experimental study. Special attention has been paid on whether the integrated system could achieve an energy-efficient and comfortable indoor environment. A typical office layout is simulated in a hot box equipped with TABS ceiling and diffuse ceiling panels. The performance of integrated system is evaluated under different boundary conditions, including weather, internal heat load, TABS activation mode. The cases without diffuse ceiling are used as reference to estimate the effect of diffuse ceiling on the air distribution and heat exchange.

2. Experimental investigations

2.1. The hot box

The study was made as full-scale experiments in a hot box located in a laboratory. According to EN ISO 8990 [23], two types of hot box apparatus are introduced: guarded hot box (GHB) and calibrated hot box (CHB). In this study, the constructed hot box was designed based on the GHB concept. Fig. 1 shows the vertical section view of the hot box. The hot box is separated into a cold chamber representing the outdoor climate and a hot chamber representing a two-floor office building. The hot chamber is divided into three different zones. The lower zone represents a two-person office where the thermal comfort and energy performance are mainly