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# Experimental investigation of cooling performance of a novel HVAC system combining natural ventilation with diffuse ceiling inlet and TABS

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ABSTRACT

A novel HVAC system combining natural ventilation with diffuse ceiling inlet and thermally activated building systems (TABS) has the ability to fulfill the requirements of cooling and ventilation in future Danish office buildings. In order to study the cooling performance of this system, a test chamber is constructed in a way to represent the characteristics of an office room. Twenty cases are tested under steady-state conditions, including ten cases without ceiling panel and ten cases with ceiling panel. An energy balance analysis shows that the tests have quite good accuracy, with an error of less than 10%. Both the cooling capacity of TABS and the influence of ceiling panel are investigated. The *U*-value of TABS water side to the room side is almost constant, but the effectiveness of TABS decreases with log mean temperature difference (LMTD) for both cases with and without ceiling panel. The radiant heat transfer coefficient of TABS is reduced by the ceiling panel whereas the convective heat transfer coefficient increases with the ventilation rate and the inlet air temperature. Experimental data is used to evaluate the thermal performance of this system, and it is also beneficial to the design of this system.



## 1. Introduction

The building sector demands regarding energy conservation have been growing for many years around the world. In general, less energy use for HVAC systems is required but without compromising a comfortable and healthy indoor environment. In order to comply with the minimum requirements for the energy performance of new buildings, constructions with low heat transfer coefficients are used and air penetration through the envelope is reduced [1], resulting in well-insulated and air-tight buildings. This approach is essentially beneficial in decreasing the heating need, but it also leads to an increasing cooling demand in buildings in both summer and winter.

With the aim of meeting the probable cooling demand during the whole year especially in winter seasons in future Danish office buildings, Yu et al. [2] have proposed a novel system that combines natural ventilation with diffuse ceiling inlet and thermally activated building systems (TABS). The Danish Design Reference Year [3] shows that Denmark has a cold climate with relatively low air temperatures even in summer and an annual mean wind speed of 4.4 m/s, which makes natural ventilation feasible in the proposed system. Therefore, this combined system has the potential of fulfilling the demands of cooling and ventilation all year with very low energy use. Fig. 1 demonstrates the schematic diagram of this solution. Outside air is supplied through controlled vents to the plenum between the concrete slab and the acoustic diffuse ceiling. After the circulation and heat exchange in the plenum, this air enters into the room space through small holes located in the diffuse ceiling. In this way natural ventilation is used to ventilate and cool the building, even in cold winter periods without any risk of draught. Meanwhile, TABS can provide the extra heating and cooling need during extreme seasons and peak hours. Thus, this new system has the potential of considerably reducing energy use and creating a comfortable indoor environment. The studies by Yu et al. [2,4] showed that for typical Danish office buildings with an internal heat load level of 30–40 W/m$^2$, without any compromise of thermal comfort, the primary energy saving potential of this integrated system can reach up to 50% compared with the other traditional air-based systems and radiant systems.

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## Nomenclature

| | |
|---|---|
| $A$ | construction area ($m^2$) |
| ACH | room air change rate ($h^{-1}$) |
| AUST | average unheated surface temperature (°C) |
| $C_{pa}$ | air specific heat capacity [J/(kg K)] |
| $C_{pw}$ | water specific heat capacity [J/(kg K)] |
| $F_{s-j}$ | view factor between slab surface and internal surface $j$ |
| $F_{\varepsilon_{s-j}}$ | radiation interchange factor |
| $h_c$ | convective heat transfer coefficient of slab surface [W/($m^2$ K)] |
| $h_r$ | radiant heat transfer coefficient of slab surface [W/($m^2$ K)] |
| $h_{tot}$ | total heat transfer coefficient of slab surface [W/($m^2$ K)] |
| LMTD | logarithmic mean temperature difference (°C) |
| $\dot{M}_w$ | TABS water mass flow rate (kg/s) |
| NTU | number of transfer units |
| $\dot{Q}_{c\text{-cond}}$ | heat conduction of diffuse ceiling (W) |
| $\dot{Q}_{ceil}$ | heat transmission from the slab when TABS is not activated (W) |
| $\dot{Q}_{ceil\text{-}t}$ | total cooling capacity through diffuse ceiling (W) |
| $\dot{Q}_{conv}$ | convective heat transfer between TABS and room/plenum air (W/$m^2$) |
| $\dot{Q}_{c\text{-}V}$ | ventilation cooling through diffuse ceiling (W) |
| $\dot{Q}_{fa}$ | heat transmission from the facade (W) |
| $\dot{Q}_{fl}$ | heat transmission from the floor (W) |
| $\dot{Q}_{hs}$ | total power of heat sources (W) |
| $\dot{Q}_{iw}$ | heat transmission from interior walls (W) |
| $\dot{Q}_{NV}$ | heat loss/gain from natural ventilation (W) |
| $\dot{Q}_r$ | radiant heat transfer between TABS and other internal surfaces (W/$m^2$) |
| $\dot{Q}_{TABS}$ | heat transmission from TABS to the test room (W) |
| $\dot{Q}_{TABS\text{-}tot}$ | total energy delivered by TABS (W) |
| $\dot{Q}_{TABS\text{-}up}$ | heat loss from TABS to upper zone (W) |
| $\overline{\dot{Q}}$ | heat unbalance rate (%) |
| $\Delta\dot{Q}$ | error of heat balance (W) |
| $T_j$ | temperature of the internal surface $j$ (°C) |
| $T_s$ | mean lower surface temperature of all slabs (°C) |
| $t_a$ | room air temperature (°C) |
| $t_{aex}$ | exhaust air temperature (°C) |
| $t_{ain}$ | inlet air temperature (°C) |
| $t_{ap}$ | plenum air temperature (°C) |
| $t_{au}$ | upper zone air temperature (°C) |
| $t_{c\text{-down}}$ | lower surface temperature of ceiling panel (°C) |
| $t_{c\text{-up}}$ | upper surface temperature of ceiling panel (°C) |
| $t_e$ | cold chamber air temperature (°C) |
| $t_{op}$ | operative temperature in the room/plenum (°C) |
| $t_s$ | temperature of the interior surface (toward the room) of the construction (°C) |
| $t_{sur}$ | mean upper surface temperature of all slabs (°C) |
| $t_{surd}$ | surrounding zone air temperature (°C) |
| $t_{wre}$ | TABS return water temperature (°C) |
| $t_{wsu}$ | TABS supply water temperature (°C) |
| $U$ | heat transfer coefficient of the construction and air film or TABS [W/($m^2$ K)] |
| $V$ | room volume ($m^3$) |

*Greek symbols*

| | |
|---|---|
| $\sigma$ | Stefan-Boltzman constant, $5.67 \times 10^{-8}$ W/($m^2$ $K^4$) |
| $\lambda$ | thermal conductivity of ceiling panel (W/m K) |
| $\delta$ | thickness of ceiling panel (m) |
| $\rho$ | air density (kg/$m^3$) |
| $\varepsilon$ | effectiveness of TABS or emissivity of surface |

This system mainly focuses on meeting the cooling demand in future office buildings. Both natural ventilation and TABS can meet the cooling demand, and the optimum combination of them can ensure a good thermal environment with the minimum energy use. The majority of previous studies [5–11] mainly focused on the energy performance of individual TABS or ventilation assisted TABS, and there were very few investigations of the acoustic ceiling fully-covered TABS. Due to the diffuse ceiling panel, natural ventilation directly interacts with TABS, resulting in a more complex thermal phenomenon inside the plenum. The individual TABS have a limited cooling power as a result of the concerns of condensation and radiation asymmetry [12], and it is more difficult to evaluate this capacity when considering the effect of ceiling panel and natural ventilation. The diffuse ceiling panel is made of wood shavings combined with cement paste; accordingly, it behaves as an insulation layer. The ceiling panel may influence the heat transfer between TABS and the room (mainly radiant heat transfer) even though a large covering percentage still provides a significant cooling from the ceiling to the room [13–16]. However, since the ventilation air circulates in the plenum before entering into the lower room, the convective heat transfer may be increased. Some analytical or experimental studies on ceiling cooling under different ventilating conditions show that the ceiling cooling capacity increases by approximately 5–35% [17–19], but the ventilation air was handled for designated conditions. Since the ceiling panel and natural ventilation may have a large effect on the energy performance of TABS, detailed analyses of the total cooling capacity and the radiant and convective heat transfers are indispensable.

The heat transfer between typical TABS and room space fundamentally consists of convection and radiation. Radiant heat transfer is largely dependent on the surface temperatures and the radiant heat transfer coefficient. The radiant heat transfer coefficient is readily obtained by measurements or calculations, and in most cases it is between 5.4 and 6.2 W/($m^2$ K) [20–22]. The convective heat transfer is determined by the air temperature, surface temperature and the convective heat transfer coefficient of the radiant surface. Because of the complicated air flow around the radiant surface in terms of air velocity and air turbulence, it is extremely difficult to measure the convective heat transfer coefficient. According to previous studies [23–29], it varies within a large range. The

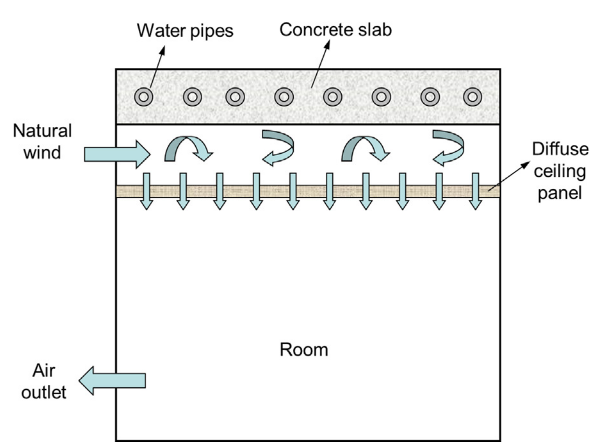


**Fig. 1.** Schematic diagram of the new system [2].