

The effect of diffuse ceiling panel on the energy performance of thermally activated building construction

Chen Zhang^{1,*}, Per Heiselberg¹ and Michal Pomianowski¹

¹Department of Civil Engineering, Aalborg University, Denmark

*Corresponding email: cz@civil.aau.dk

ABSTRACT

An integrated system combining diffuse ceiling ventilation with thermally activated building construction (TABS) was proposed recently. In this system, TABS is encapsulated by diffuse ceiling panel and cannot have directly heat exchange with the room. The aim of this study is to investigate the effect of diffuse ceiling panel on the energy performance of TABS in both heat and cooling mode. Experiments are carried out in a full-scale test facility with the integrated system, and the cases without diffuse ceiling are also measured as references. The results indicate that the diffuse ceiling has an opposite effect on the heating and cooling capacity of TABS. In addition, a numerical model is built and validated by the measured data. The validated model is further applied to conduct a paramedical study on the materials of the diffuse ceiling panel.

KEYWORDS

Diffuse ceiling ventilation, TABS, Experiment, CFD

INTRODUCTION

A novel HVAC system was proposed recently which combines diffuse ceiling ventilation and thermally activated building constructions (TABS) (Yu, 2014). The schematic diagram of the system is illustrated in Figure 1. In the system, the space between TABS and the diffuse ceiling is used as a plenum and the fresh air is supplied into the occupied zone through perforations in the diffuse ceiling panels. Due to the large inlet area of diffuse ceiling, air is delivered into the occupied zone with very low momentum. Therefore, the system can avoid draught risk even by directly supplying outdoor air in winter (Hviid, 2013; Zhang, 2015). On the other hand, the plenum is employed to distribute air instead of running ducted system. The pressure loss is small between the plenum and the room, making the use of natural ventilation possible. TABS is a radiant system with water-carrying pipes embedded into building constructions. TABS could work as a passive system to remove peak load by making use of the thermal mass of concrete slabs. Alternatively, in extreme summer or winter weather conditions, when ventilation is not sufficient to provide an acceptable indoor environment, it could be activated as a supplementary system to deal with excessive cooling or heating demand. The integrated system aims to provide cooling/heating and ventilation to office rooms all year around.

Although the individual technique of diffuse ceiling ventilation and TABS have been researched and applied in many buildings, the concept of the integrated system is new and needs a comprehensive investigation. One key issue is the harmony of these two techniques. According to B. Olesen (2012), the optimal capacity of TABS is obtained when there is a free heat exchange between concrete slabs and space, which requires as much of the TABS surface exposed to the rest of room as possible. However, in the integrated system, diffuse ceiling panels cover the TABS surface, consequently, influence the heat exchange between TABS

The air permeable diffuse ceiling is made by the wood-cement board which normally use for the acoustic purpose. The ceiling panels are installed 0.35 m below the concrete slabs by a suspension system, which separates the lower zone into a ceiling plenum and a conditioned space as shown in Figure 4. The ceiling panels have a thickness of 35 mm and porosity of 65%. The thermal conductivity of the ceiling panels is 0.085 W/m.K, measured by λ -Meter EP500 based on a guarded hot plate method.

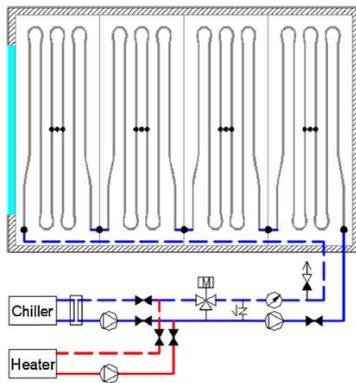


Figure 3. TABS with water circuit



Figure 4. Diffuse ceiling panels and TABS

The case setup and measurement

The aim of the experimental study is to explore the impact of diffuse ceiling panel on the energy performance of TABS. Therefore, the cases without diffuse ceiling are used as references. The experiments are carried out in both heating and cooling conditions and with different heat loads and airflow rates. The detail of boundary condition is shown in Table 1.

Table 1. Boundary conditions for different cases.

| Case | Air change rate h^{-1} | Supply air temperature $^{\circ}\text{C}$ | Heat load W | TABS water supply temperature $^{\circ}\text{C}$ | TABS water flow rate m^3/h | Diffuse ceiling |
|------|------------------------------------|--|----------------|---|---|-----------------|
| 1 | 2 | -7.10 | 450.5 | 36.38 | 135 | - |
| 2 | 2 | 23.82 | 450.5 | 17.29 | 140 | - |
| 3 | 4 | -6.87 | 914.5 | 38.91 | 208 | - |
| 4 | 4 | 23.89 | 914.5 | 10.95 | 273 | - |
| 5 | 2 | -6.87 | 450.5 | 30.89 | 136 | Y |
| 6 | 2 | 24.1 | 450.5 | 8.10 | 221 | Y |
| 7 | 4 | -7.23 | 914.5 | 35.63 | 138 | Y |
| 8 | 4 | 24.07 | 914.5 | 4.27 | 294 | Y |

To measure surface temperature of concrete slabs, three thermocouples are located at the lower surface (Figure 3) and one thermocouple is placed on the upper surface for each slab. Water temperatures are measured at five points, including supply and return for each slab, as indicated in Figure 3. The water flow rate is recorded by a Brunata HGQ flow meter. Besides the measurements regarding TABS system, the air temperature and operative temperature in the room, the surface temperature of building envelope and diffuse ceiling panels and air velocity in the occupied space are measured in this study.

Experimental results and analyses

TABS separates the test chamber into a lower zone and an upper zone, therefore, the heat release by TABS Q_{TABS} transfer to both zones. The energy balance of TABS under steady-state is expressed by Eq (1):

$$Q_{TABS} = Q_{TABS,up} + Q_{TABS,down} \quad (1)$$

The total heat release by TABS can be determined by the energy flow within the water pipe. Since the pipe located far away from the upper surface, the temperature is almost evenly distributed on the upper surface. Therefore, the heat delivered to the upper zone can be calculated by the temperature difference between upper zone $t_{a,up}$ and TABS' upper surface $t_{s,up}$. The heat delivered to the lower zone $Q_{TABS,down}$ is expressed by the equation below:

$$Q_{TABS,down} = C_{p,w} \cdot M_w \cdot (t_{w,su} - t_{w,re}) - h_{ins} \cdot A \cdot (t_{s,up} - t_{a,up}) \quad (2)$$

Where: $C_{p,w}$ is the specific heat of water, M_w is the water flow rate, $t_{w,su}$ and $t_{w,re}$ are supply and return water temperature, h_{ins} is the heat transfer coefficient of insulation layer above the TABS. The heat transfer coefficient is an important parameter to evaluate the energy performance of a radiant system, which presents the relationship between heat flow intensity and the temperature difference between room and average surface temperature. The heat transfer coefficient h_{TABS} between TABS and the room is expressed by Eq (3), based on the operative temperature at 1.1 m height T_{op} and the average temperature of TABS lower surface $T_{s,avg}$.

$$h_{TABS} = \frac{Q_{TABS,down}}{A \cdot (T_{op} - T_{s,avg})} \quad (3)$$

Table 2 presents the experimental results of the energy performance of TABS. It is evident that the impact of the diffuse ceiling on the heating/cooling capacity of TABS is significant. The heat transfer coefficients in the cases without diffuse ceiling are about 4.4 W/m².K for heating and 7.7 W/m².K for cooling, which are close to the recommended design values presented by EN 15377-1(2008). However, the values in the cases with diffuse ceiling show a different manner, which is around 13 W/m².K for heating and 2.4 W/m².K for cooling.

Table 2. Energy performance of TABS in the cases with and without diffuse ceiling

| Energy terms | Without diffuse ceiling | | | | With diffuse ceiling | | | |
|----------------------------------|-------------------------|---------|--------|----------|----------------------|---------|---------|----------|
| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 | Case 8 |
| Q_{TABS} [W] | 651.52 | -521.95 | 897.93 | -1034.93 | 567.45 | -598.34 | 1067.91 | -1020.52 |
| $Q_{TABS,up}$ [W] | 95.07 | -49.06 | 125.18 | -113.79 | 42.23 | -168.01 | 56.47 | -209.41 |
| $Q_{TAB,down}$ [W] | 556.45 | -472.89 | 772.75 | -921.14 | 525.23 | -430.32 | 1011.44 | -811.11 |
| h_{TABS} [W/m ² .K] | 4.45 | 7.67 | 4.37 | 7.68 | 11.64 | 1.94 | 14.22 | 2.85 |

From the view of heat transfer mechanism, TABS exchanges heat with the room through both radiation and convection. As an obstacle between TABS and the rest of the room, diffuse ceiling changes the airflow pattern near the TABS surface and also changes the view factor between TABS and the other room surfaces. In the heating cases, the heat transfer coefficients are promoted by using diffuse ceiling. This can be attributed to that cold outdoor air is forced to contact with warm TABS surface, which gives a larger air-surface temperature difference

and relatively high air velocity near TABS surface. Thus, the increase of convective heat transfer offsets the loss of radiative heat transfer. On the contrary, the air-surface temperature reduces in the cooling cases. Consequently, both convection heat exchange and radiation heat exchange are declined by the existence of diffuse ceiling. As a result, TABS need to run with a much lower surface temperature in the cooling cases, to keep an acceptable indoor air temperature. This explains why TABS water temperature is down to 4 °C after installing the diffuse ceiling, much lower than the recommended water supply temperature of 18 °C to 20 °C (Olesen, 2012). Operating at such low water temperature eliminates TABS' advantage on high-temperature cooling and raises condensation risk of the system.

NUMERICAL STUDY

Description of the CFD model

The numerical study uses a CFD model to solve the airflow and temperature distribution in the plenum and occupied space. Since determining the energy performance of TABS is one of the primary objectives of this study, heat flux through TABS surface is an important parameter to investigate. Two numerical models regarding diffuse ceiling ventilation were built and compared by Zhang et al. (2015), one is a simplified geometrical model and the other is porous media model. Although the porous media model gave better predictions on the flow characteristic through the diffuse ceiling supply, this model presented a limitation on calculating the radiant heat exchange which is the focus of this study. Therefore, the simplified geometrical model is applied here.

A simplified geometrical model

A simplified geometrical model is a common approach to simulate air diffusers, which is to replace the complex diffuser by one or more simple rectangular slots. The effective opening area of the diffuse ceiling diffuser is related to the panels' porosity, but also depends on the shapes of the pores in the media and their level of connectedness. The effective opening area is calculated based on the pressure drop results obtained by measurement, and expressed by Eq (4):

$$C_d A = \frac{\dot{m}}{\sqrt{2\rho\Delta P}} \quad (4)$$

A default C_d value of 0.6 is used in this study, which is suitable for the opening with low area ratio. Therefore, three slots opening with an effective area of 0.032 m² each are built to simulate the air passage of diffuse ceiling ventilation.

The thermal process within the plenum is complex, which includes both the convective heat exchange between supply air and thermal mass and radiative heat exchange between diffuse ceiling panels and TABS. Therefore, a surface-to-surface radiation model is activated in this model.

Boundary conditions and numerical methods

The CFD model is built to represent the test chamber as it physically. Three small windows above the diffuse ceiling serve as inlet (Figure 4) and a ventilation duct located on the lower corner of façade serves as an outlet. In order to simplify the geometrical model and generate high-quality structure meshes, the inlet and outlet are simplified as rectangular openings with the same opening area as in the experiments. The inlet is set up as a velocity inlet which has uniform profiles on the air temperature and air velocity. The outlet is simulated with zero pressure and zero gradient conditions for all flow parameters. The wall boundaries are

specified by the U-value together with the measured air temperatures in the climate chamber and surrounding zone (or called free stream temperature). The ceiling slab is defined by a uniform surface temperature. The total heat leased by the heat sources are treated as surface heat fluxes on the manikins, computers, and task lamps.

The airflow goes through the diffuse ceiling with very low velocity, which could regards as laminar flow. However, the convective flow generated by heat sources increase the turbulence level in the room. Re-normalized group (RNG) k- ϵ model is recommended in this situation, as reported by Zhang et al. (2007).

Structure meshes are generated in the entire computational domain and the finest meshes are generated in critical areas such as: diffuse ceiling, inlet, outlet, area close to the walls and heat sources. Grid independent check is performed by modelling with different cell amounts. The cell amount of 741,831 can achieve accuracy results, increasing the grids does not lead to a significant improvement but require much more computing time and computational resources. The SIMPLE numerical algorithm is used. The criteria of convergence are set such that the residuals for u , v , w , k , ϵ are less than 10^{-3} , and the residual for energy is less than 10^{-6} .

Validation of the CFD model

The CFD simulations are performed in case 5 and case 6. Due to the limited space available in this paper, the comparison of the simulated results on the air temperature and velocity distribution with the corresponding experimental data will not be presented here, where the detailed information can be found in Zhang et al. (2015).

Table 3 shows the comparison of the heat flow from TABS to the lower zone between experiment and CFD simulation. Although measurement cannot split the total heat flow into heat transfer through convection and radiation, the CFD model is able to provide more detailed information. A good agreement has been reached between the simulated results and measured data for the total heat flow from TABS to the lower zone, where the deviations are less than 10% in both cases. Therefore, the CFD model can be considered reliable and further used to conduct sensitivity study on selected design parameter.

Table 3 Comparison of heat flow from TABS to the lower zone

| Case | Method | Convective | Radiative | Total heat | Deviation |
|--------|----------|----------------|----------------|------------|-----------|
| | | heat flow W | heat flow W | flow W | |
| Case 5 | Measured | - | - | 525.23 | 1.64% |
| | CFD | 205.09 | 311.52 | 516.61 | |
| Case 6 | Measured | - | - | -430.32 | 7.16% |
| | CFD | -288.82 | -172.29 | -461.11 | |

Parameter study

In the integrated system, TABS is encapsulated by the diffuse ceiling. Therefore, the properties of diffuse ceiling panel have a remarkable impact on the TABS's thermal performance. Two types of diffuse ceiling panels are analysed in this study: one is wood-cement panel as used in the experiment and the other is aluminium (Al) panel. The reason to choose Al panel as an example is that it is the most commonly used suspended ceiling in the practice and it has significantly higher conductivity compared with wood-cement panel. As a matter of fact, the diffuse ceiling served as a layer of insulation between the TABS and room. The change in thermal resistance consequently leads to the change in the heat transfer

between these two zones. The thermal conductivity of wood-cement panel is 0.85 W/m.K and of the Al panel is 202.4 W/m.K. In order to limit the number of variables, it is assumed that both diffuse ceiling panels have the same thickness and porosity in the CFD models. In addition, to avoid the influence of material emissivity on the radiative heat exchange, it is assumed that the Al panels are painted and have the same emissivity as the wood-cement panels.

Table 4 presents the CFD results with two different diffuse ceilings in both heating and cooling cases. It is clear that the increase of thermal conductivity plays a beneficial role in the cooling performance of the TABS. The heat transfer coefficient increases from 2.18 W/m².K to 3.18 W/m².K by replacing wood-cement panels with Al panels. This can be explained by that Al panels enable a higher temperature difference between plenum air and TABS surface in the cooling mode, which promotes the convective heat transfer from TABS to the lower zone. On the other hand, the surface to surface temperature difference between TABS and diffuse ceiling panels also increases by using Al panels. Therefore, promotion of the radiant heat exchange could be expected as well. However, an opposite effect is revealed in the heating mode, where the heat transfer coefficient reduces half by using Al panels. Both convective and radiative heat exchanges are weakened by using Al panels, as shown in Table 4.

Table 4. CFD results with different diffuse ceiling

| Diffuse ceiling material | T _{a.inlet} °C | T _{s.TABS} °C | T _{op.room} °C | Q _{TABS} W | Q _{TABS.rad} W | Q _{TABS.conv} W | h W/m ² .K |
|--------------------------|----------------------------|---------------------------|----------------------------|------------------------|----------------------------|-----------------------------|--------------------------|
| Wood-cement | | | 24.75 | 516.61 | 311.52 | 205.09 | 12.59 |
| Al | -6.87 | 27.34 | 23.11 | 456.57 | 260.23 | 196.34 | 6.81 |
| Wood-cement | 24.1 | 10.79 | 24.15 | -461.11 | -172.29 | -288.82 | 2.18 |
| Al | | | 21.96 | -561.96 | -237.68 | -324.28 | 3.18 |

According to the experimental study above, using of diffuse ceiling enhances TABS heating capacity but decreases its cooling capacity compared with single TABS system. The use of diffuse ceiling with high conductivity could to some extent reduce this impact. Especially for the building that cooling is the main task, using of the diffuse ceiling with high conductivity can reduce the condensation risk and increase the possibility of the usage of renewable resources for TABS system.

CONCLUSIONS

This paper investigates the effect of diffuse ceiling panels on the energy performance of TABS. Experiments are carried out in a full-scale test facility under different boundary conditions, including TABS operative modes and with/ without a diffuse ceiling. The results indicate that the presence of diffuse ceiling plays a different role in the heating and cooling capacity of TABS. Diffuse ceiling promotes the heating capacity of TABS but reduces its cooling capacity. This is attributed to that diffuse ceiling changes the airflow pattern near the TABS surface and view factor between TABS and the rooms, consequently, changes the convective and radiative heat exchange between the TABS and the rest of the room.

A CFD model for the integrated system is built and validated by the experimental data. The model can be used to predict the temperature and velocity distribution and also the heat flow from TABS to the room. The discrepancies between simulated and measured heat flow of TABS are less than 10%. The validated CFD model is further used to explore the impact of

different diffuse ceiling material on the energy performance of TABS. The analysis demonstrates that diffuse ceiling panel with high thermal conductivity can reduce the impact of the diffuse ceiling. For the building that cooling is the main task, diffuse ceiling with high conductivity can reduce the condensation risk and increase the possibility of the usage of renewable resources.

REFERENCE

- BS-EN-15377-1. 2008. Heating Systems in Buildings-Design of Embedded Water Based Surface Heating and Cooling Systems. Determination of the Design Heating and Cooling Capacity.
- Hviid, C. A., and Svend Svendsen. 2013. Experimental Study of Perforated Suspended Ceilings as Diffuse Ventilation Air Inlets. *Energy and Buildings* 56, 160–168.
- Olesen, Bjarne W. 2012. Using Building Mass To Heat and Cool. *ASHRAE Journal*, 44–52.
- Yu, Tao et al. 2014. A Novel System Solution for Cooling and Ventilation in Office Buildings: A Review of Applied Technologies and a Case Study. *Energy & Buildings* 90, 142–155.
- Zhang, Chen, Per Kvols Heiselberg, et al. 2015. Experimental Study of Diffuse Ceiling Ventilation Coupled with a Thermally Activated Building Construction in an Office Room. *Energy and Buildings* 105, 60–70.
- Zhang, Chen, Qingyan Chen, et al. 2015. Airflow Pattern and Performance Analysis of Diffuse Ceiling Ventilation in an Office Room Using CFD Study. In: *Proceedings of 14th Building Simulation Conference*, Hyderabad, India.
- Zhang, Zhao, Wei Zhang, et al. 2007. Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part-2: Comparison with Experimental Data from Literature. *Hvac&R Research* 13(6): 853–870.