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Thermo-active building systems and sound absorbers: Thermal comfort under real operation conditions

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ABSTRACT

Radiant systems are established today and have a high ecological potential in buildings while ensuring thermal comfort. Free-hanging sound absorbers are commonly used for room acoustic control, but can reduce the heat exchange when suspended under an active slab. The aim of this study is to evaluate the impact on thermal comfort of horizontal and vertical free-hanging porous sound absorbers placed in rooms of a building cooled by Thermo-Active Building System (TABS), under real operation conditions. A design comparing five different ceiling coverage ratios and two room types has been implemented during three measurement periods. A clear correlation between increase of ceiling coverage ratio and reduction of thermal comfort could not be derived systematically for each measurement period and room type, contrarily to what was expected from literature. In the first two monitoring periods in the larger office rooms, rooms with higher coverage ratios reported higher operative temperatures. This correlation was however not clear from the monitoring in the smaller offices and other measurement periods. In all monitored rooms, a strong influence of the user behaviour on thermal comfort has been observed. A higher temporal offset between ceiling and operative temperature was also observed in rooms equipped with absorbers.

1. Introduction

As buildings are estimated to account for approximately 40% of global energy consumption today [1], the building industry has a clear role to play in lowering its environmental footprint. At the same time, the main function of a building is to provide a healthy and comfortable indoor environment for the occupants. In this context, hydronic radiant surface heating and cooling technologies have the potential to achieve significant energy savings [2] while maintaining optimal indoor comfort conditions. An example of such system are Thermo-Active Building Systems (TABS), that benefit from activating and controlling the building thermal mass by means of heated or chilled water through pipes embedded in the concrete slabs exposed to the indoor environment. The system will exchange heat with the room primarily through thermal radiation (at least 50%) between the conditioned surface and the surrounding room surfaces – weighted by the corresponding view factors – as well as by convection [3]. To preserve the heat transfer, the radiant surfaces (commonly the ceiling surface) are left exposed. This is not in alignment with the need for room acoustic comfort. Indeed, sound absorption on the ceiling is often required to reduce sound reverberation, sound propagation and address speech intelligibility. In this study, room acoustic comfort is achieved by varying the coverage ratios of horizontal hanging sound absorbers of 30, 45 and 60%, and compared to vertical absorbers in an arrangement corresponding to a coverage ratio of 60%. How covering TABS ceilings with acoustic panels can help to achieve both thermal comfort while being in line with acoustic guidelines and requirements (in Germany) is described in Ref. [4].

Ensuring occupant comfort at every level is an important part of the design process, and attention should be paid on finding ways to overcome the challenges between thermal and acoustic comfort. In situations where a fully-covering sound-absorbing ceiling is not conceivable or desired, free-hanging sound absorbers, horizontal or vertical can be implemented. However, it is important to quantify the effect that such elements will have on the cooling capacity of TABS and, by means of consequence, how they impact room thermal comfort. Different authors

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Abbreviations

A	total amount of absorption (sum of all equivalent absorption areas in room)
α_w	Sound absorption coefficient
EAA	Equivalent Absorption Area
ORT	Operative Room Temperature
PMV	Predicted Mean Vote
RT	Reverberation Time
t_a	Air temperature
$\bar{t}_r$	mean radiant temperature
TABS	Thermo-Active Building Systems
USS	Use of Solar Shading
WO	Window Opening

have studied the effects of sound absorbers on the cooling performance of TABS, by means of measurements in climatic chambers [5–11], field measurements [12] and more recently by means of numerical building simulations [5,13–15]. Furthermore, several studies and surveys have been conducted to analyse the satisfaction of occupants with the acoustic conditions in TABS (office) buildings [16–19].

Weitzmann et al. [11] analysed under steady-state conditions in a climatic chamber the interdependencies of TABS cooling capacity and ceiling-mounted acoustical clouds for different ceiling coverage ratios and layouts, and showed that effective cooling from TABS and partially-covering acoustical ceiling were not mutually exclusive. Pittarello [9] reports a reduction of the TABS cooling capacity coefficient of 12% and 22% for ceiling coverage ratios of 35% and 70% respectively. The author also reported a subsequent operative temperature increase of 2 K in this latter situation compared to a reference case. The results also showed that using vertical sound absorbers did not lower the cooling capacity noticeably. Peperkamp and Vercammen also studied the effects of horizontal sound absorbers on the cooling capacity of TABS with various ceiling coverage ratios. In Ref. [8], they quantify a reduction in cooling capacity of 20–25% for a ceiling surface covered with 50% of sound absorbers, and down to a reduction of 40% at a coverage of 85%. Overall, they conclude that the reduction of the radiative part of the thermal capacity is less than the percentage of ceiling coverage ratio. In Ref. [7], Peperkamp performed measurements in a climatic chamber. With an effective coverage of approximately 58% achieved by panels evenly distributed over the ceiling surface, the experiment concludes on a reduction of the heat output delivery of approximately 33%. Interestingly enough, this reduction increases to 38% in the case of panels clustered altogether at the centre of the room, with the same coverage ratio. Ruud [10] reports a cooling capacity reduction of 20% with panels covering 60% of a radiant chilled ceiling. Karmann et al. [6] also studied a radiant chilled ceiling and report a cooling capacity reduction of 11% for acoustical clouds covering 47% of the ceiling surface.

Dominguez et al. [5] report a decrease of the cooling performance of a TABS ceiling in a climatic chamber of 11%, 23% and 36% for ceiling coverage ratios of 43%, 60% and 80% respectively with horizontal sound absorbers. This study also investigated experimentally the situation of vertical sound absorbers, reporting respective cooling performance drops of 8%, 12% and 14%. This decrease in cooling translates in a room operative temperature increase of 0.6 K, 1.5 K and 1.6 K respectively for coverage ratios of 43%, 60% and 80% with horizontal absorbers; and 0.5 K, 0.9 K and 1.1 K for vertical absorbers.

Lombard [13] developed a numerical model accounting for the presence of free-hanging horizontal sound absorbers placed under a cooled ceiling, which can be implemented in building simulation software. Using this tool, Rage et al. [14,15] created a numerical model of a climate chamber equipped with TABS slabs and horizontal hanging sound absorbers. The authors validated the model with existing measurements [15] and used this validated model to carry out sensitivity analyses [14]. This model was also used in Ref. [5] to compare with the experimental setup. The simulated case was able to closely predict the cooling performance reduction, air and operative temperatures and ceiling surface temperature measured in the climate chamber. Langner and Bewersdorff [20] simulated the effects of horizontal sound absorbers on the thermal and acoustic indoor environment in an open-plan office cooled by TABS. The authors showed that the room temperatures were not affected significantly up to a ceiling coverage ratio of 50%, and that a ceiling coverage ratio of more than 60% was necessary to exceed a room temperature of 25 °C significantly.

In the context of the interdependency of TABS and acoustic panels, most of the scientific knowledge available was drawn from controlled laboratory experiments and numerical simulations. Relatively few studies have been performed to quantify the influence of using sound absorbers with TABS under real operation conditions. One can cite the field study of Le Muet et al. [12] conducted in an office building in use in France. The building is cooled by TABS and the authors suspended varying quantities of horizontal absorbers underneath. The authors showed that the operative temperature increased by 0.3 K when the ceiling coverage ratio was 50% and by 0.8 K when the ceiling coverage ratio was 70%.

The present study was therefore designed as a case study in a TABS office building in use in Freiburg, Germany. The aim is to evaluate the influence of horizontal and vertical free-hanging porous sound absorbers on the thermal indoor environment of rooms cooled by TABS under real operation conditions. The study is thereby also providing valuable input for understanding the interdependencies of occupant behaviour, thermal comfort, energy consumptions and good acoustics, which is a major challenge in building simulation and developing reliable building models, both for simulations studies but also in planning processes. The challenges, influence of occupant behaviour and lack of knowledge is described and addressed in i.a [21–28].

For this purpose, six office rooms of two different sizes but of comparable occupancy rate and use were monitored simultaneously, with increasing amount of free hanging porous absorbers (0, 30, 45 and 60% of the ceiling surface). Three consecutive monitoring periods of four weeks each have been performed, which consisted of changes in the coverage ratios and types of absorbers used. This comparative design allowed for evaluation of the effect of ceiling coverage ratio, type of absorber and repeatability of the experiment.

2. Methods

In the following, the methods used for the monitoring of thermal comfort performed in this study are described.

2.1. Field study: monitoring thermal comfort under real operation conditions

The monitoring was carried out in an office building, built in 2010. The building has a net area of 811 m^2 and 21 office rooms per floor, oriented from South-West to North-East. The external walls have a U-value of 0.21 W/(m^2.K) and the windows of 1.3 W/(m^2.K). The building is cooled during summer by a hydronic thermo-active cooling system where the pipe system is integrated in the concrete ceiling (20 mm diameter, 150 mm spacing, and placed 40 mm from ceiling surface). The system is designed for a supply temperature of 16 °C and a temperature difference between supply and return of 2 K. The building has a mechanical ventilation system with heat recovery and the air exchange rate is 1 h^{-1}. Additionally, windows can be opened manually by the occupants. The rooms are equipped with exterior solar shading (venetian blinds), which are automatically controlled (irradiation,

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