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Cooling capacity and acoustic performance of radiant slab systems with free-hanging acoustical clouds

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ABSTRACT

Radiant slab systems have the potential to achieve significant energy savings, yet, when applied in the ceiling (e.g., thermally activated building system) the exposed concrete may also create acoustical challenges due to the high reflectivity of the hard surface. Balancing all of the building indoor environmental quality factors is important in the design of an effective workspace for the occupants, and so we need to consider the interactions between thermal and acoustic comfort. We assessed the cooling capacity in a hydronic test chamber and the sound absorption in a reverberation chamber to study the effects, for an office room, of different coverage areas of free-hanging acoustical clouds below a radiant chilled ceiling. The cooling experiments showed that for 47% cloud coverage of the ceiling area, we measured only an 11% reduction in cooling capacity caused by the blockage of radiant exchange between the ceiling and the room. The acoustical results showed that if the cloud covered 30% of the ceiling in a private office or 50% in an open plan office, acceptable sound absorption at the ceiling was achieved. We showed that good acoustic quality can be achieved with only a minor reduction of cooling capacity.

1. Introduction

Radiant slab systems have the potential to achieve significant energy savings primarily due to the use of lower temperature differences between the space and the heating or cooling source and the possibility to store energy in the slab [1]. This allows for higher efficiency at the device that generates hot or cold water, such as a boiler or chiller. In some cases, the relatively lower chilled water temperatures may eliminate the need for a chiller altogether, thereby enabling the use of non-refrigerant cooling sources, such as ground water, cooling towers, or indirect evaporative coolers. The use of water as the circulating fluid instead of air also reduces the energy costs of transferring heat to or from the space. Lastly, the thermal inertia inherent in a radiant slab system also provides opportunity for peak demand reduction and load shifting [2–6,1]. However, the low temperature differences require large surfaces to ensure heat exchange with the space. As a result, designers typically implement radiant systems on the largest surfaces in the space (e.g., ceilings or floors).

By definition, a radiant heating and cooling system exchanges at least 50% of its heat through thermal radiation [7]. Radiant heat exchange between surfaces involves view factors, which represent the proportion of the radiation that leaves a first surface that strikes a second surface. To preserve heat transfer (and avoid compromising view factors), it is desirable to keep radiant systems uncovered. In the case of a commercial building, this is in direct conflict with the need to add acoustic absorption in the ceiling plane to improve the acoustic quality of the space. A suspended acoustical ceiling is the least expensive approach to adding sound absorption but it also requires a large surface area to be effective for reverberation control within the space. Practitioners have identified this conflict as a barrier for the implementation of radiant systems [8]. Occupant satisfaction studies conducted in buildings using radiant systems are commonly showing lower acoustic satisfaction compared to non-radiant buildings [9] proving that acoustic quality in buildings using radiant systems needs to be addressed.

All materials have the ability to absorb and reflect sound. Acousticians refer to the sound absorption coefficient as an indicator of the fraction of sound energy absorbed by a surface. Sound absorption coefficients depend on frequency and their value varies between zero (a perfectly reflective surface) and one (a perfectly absorptive surface). Massive radiant types such as thermally active

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Nomenclature

A	Area (m^2)
cp_w	Water specific heat capacity (KJ kg^{-1} K^{-1})
q	Heat transfer rate (W)
q''	Heat flux (=q/Arad) (W m)
P	Power (W)
$\dot{m}$	Water mass flow rate (Kg s^{-1})
U_{cc}	Cooling capacity coefficient (W m^{-2} K^{-1})
t	Temperature in °C (°C)
T	Temperature in k (K)
t_a	Air temperature (°C)
t_{op}	Operative temperature (°C)
t_{mr}	Mean radiant temperature (°C)
tg	Globe temperature (°C)
$t_{w,s}$	Water supply temperature (°C)
$t_{w,r}$	Water return temperature (°C)
$t_{w,m}$	Mean water temperature (°C)
ΔTw	Water temperature difference (ΔTW = tw,r − tw,s) (K)
v	Air velocity (m s^{-1})
$A_{absorption}$	Equivalent sound absorption area (Sabin, m^2)
c	Speed of sound (m s^{-1})
d	Decay rate (dB s^{-1})
T_{60}	Reverberation time (s)
V	Volume (m^3)

building systems (TABS) are made of exposed concrete, whose sound absorption coefficients are typically 0.02 over the normal frequencies [10]. This means that TABS cause excessive sound reflection in spaces, which yield too much reverberation. By contrast, porous sound absorbing materials have sound absorption coefficients typically ranging between 0.30 and 0.90 depending on frequencies and types [10]. Sound absorbing material reduce both the sound level and reverberation time, which are key factors in the design of offices for acoustic comfort.

In this study, we wanted to address the problem of poor sound absorption of TABS. We proposed to combine a radiant cooled ceiling with several configurations of free-hanging discontinuous acoustic clouds (sometimes called canopies). This type of sound absorber is known to have an increased acoustic performance compared to regular suspended ceilings due to the larger surface area exposed to sound, i.e., both the upper and lower surfaces, since sound has access to both sides of the cloud. For simplicity, when referring to ceiling coverage for these clouds, we report the perpendicular projection of the cloud on the total ceiling area. It has been reported that covering 60% of a ceiling with free-hanging cloud can have comparable performance to 100% coverage with a suspended ceiling [11]. As they are free-hanging, these clouds have an open air space above them. Air can freely circulate between the cloud and the ceiling allowing heat exchange by convection from the radiant cooled ceiling.

The combination of radiant cooled ceiling with free-hanging acoustic clouds has raised research interest over the last decade, but we did not find experimental-based peer-reviewed journal publications on this topic. The conference papers and manufacturer white papers that we found consistently showed that the reduction of cooling capacity between slab and room was small and lower than expected [12–15]. Overall, it appears that partial coverage of a radiant chilled ceiling with free-hanging clouds does not cause a proportionally equivalent reduction of the cooling capacity. Instead, the reduction in cooling capacity is 3–4 times lower than the percentage cloud coverage. This outcome opens doors to the potential combination of acoustical clouds with TABS.

The objectives of this study are to: (1) experimentally assess the effect on radiant ceiling system cooling capacity for various coverage areas of free-hanging acoustic clouds, and (2) determine the change in sound absorption for the same configurations. We conducted two laboratory studies: the first one in a certified controlled climatic chamber equipped with a radiant cooled ceiling and free-hanging clouds, and the second one in a certified reverberant chamber equipped with comparable configurations of acoustic clouds.

2. Method

2.1. Cooling capacity measurements

2.1.1. Experimental facilities and room description

We conducted the cooling capacity experiments in a climatic chamber (4.27 m × 4.27 m × 3.0 m) at Price Industries in Winnipeg, Manitoba in September 2015. The floor area of the chamber is 18.2 m^2, and the volume is 54.7 m^3. The chamber has no windows. The walls, the ceiling, and the floor have similar construction and thermal properties with an overall conductance of 0.135 W/m^2 K. Starting from the exterior the detailed wall composition includes: 3.522 m^2 K/W insulation, a stagnant 0.102 m air gap (0.352 m^2 K/W), aluminium extruded walls, 0.102 m of polyurethane board (3.522 m^2 K/W). This chamber is accredited by the EN 14240 [16] for chilled ceiling testing. It is located inside a large laboratory facility maintained at 21.6 °C ± 0.5 °C (we note that the facility temperature was not measured for the test with highest coverage (71%), which was the first experiment conducted).

We installed graphite metal radiant panels in the chamber as part of a suspended ceiling placed at a height of 2.5 m above the floor. Each radiant panel is 1.83 m long and 0.61 m wide (area equal to 1.11 m^2). Cotton fiber insulation was placed on top of the panels (2.288 m^2 K/W). In total, twelve radiant ceiling panels were centered on the ceiling, covering 73.5% (13.4 m^2) of the total area. The twelve panels were the maximum number that could be accommodated in the chamber. The intention was to represent TABS, the system of interest in this study, as near as possible by covering close to 100% of the ceiling area. We connected the panels in series in order to reduce overall measurement uncertainty (we reached lower uncertainty by increasing the temperature difference between supply and return water temperature). To ensure a more uniform distribution of surface temperatures at the ceiling level, the panels were connected in mixed order so that the average temperature of adjacent panels was similar. The chamber did not include an air system because we wanted to specifically focus on the change in cooling capacity of the radiant chilled ceiling, and adding an air system would increase overall uncertainty in the results.

Table 1 summarizes the heat sources used in the experiment. We modelled office heat sources using computers (tower CPUs), flat screens and desk lamps on the desks, and overhead lighting (0.25 m below the radiant ceiling). We simulated occupants with power-adjustable dummies according to EN 14240 [16]. When fully installed, the test chamber represented a four-person office with a computer at each workstation; a relatively high occupant density of 4.55 m^2 per person. The data acquisition system was located outside the chamber, and therefore not listed here.

We also equipped the chamber with acoustical panels made out of fiberglass pre-formed in a 1.20 m square and 0.04 m thick cloud shape. These clouds were suspended at 0.25 m below the radiant ceiling (similar to the overhead lighting) centered on the ceiling in a 3 by 3 array, 1.37 m center to center. A maximum of 9 clouds could be positioned on the ceiling with a spacing of 0.17 m between them and 0.16 m between them and the walls. The overhead lighting fixtures could fit in the space in between two clouds. Fig. 1 shows a