Performance evaluation of balanced heating and cooling with hydronic ceilings and floors

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Abstract. Climate change increases the necessity of cooling demand in European housing. Systematic solutions in building planning and construction level are essential in order to avoid retrofit air conditioning units' installations. Implementation of Low Temperature Heating and High Temperature Cooling with embedded water-based systems is gaining ground in large scale residentials projects, being already a standardised practise in the tertiary building sector. In all related systems, heat dissipation and absorption at low temperature difference to room temperature, respectively surface systems, plays a central role. Economically motivated, the combination of cooling with underfloor-heating or also heating with ceiling-cooling systems is evident. This paper analyses challenges related to the capabilities and performance limitations of these applications, concerning thermal comfort limits, potential condensation risks, system energy efficiency and reliable control strategies. The outcomes of static and dynamic heat flux simulations are presented, accompanied with a literature review and conclusions from post occupancy performance evaluation surveys of realised projects. Arguments for utilising the ceiling surface for heating and cooling predominate those of the floor usage. Furthermore, there are convincing results in favour of laying the pipes close to the surface of thermally activated building systems (TABS). Control strategies of these systems in residential building should be very simple and robust. For cooling, best performance is obtained by TABS permanently operating with a constant water flow temperature of 21°C. For heating, very simple zone thermostats, without any features of nocturnal temperature reduction or weekly schedules are sufficient. This works also supports the argument of extending the applicability range of adaptive comfort to buildings with hydronic mass activation as a system cooling

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1. Introduction

Due to the rapidly evolving climate change, European housing is increasingly confronted with the necessity of cooling demand, additive to the heating demand. If individual retrofit installation of air conditioning units (ACU) is to be prevented, systematic solutions are essential in building level [1, 2].

Beyond comfort, the seasonally balanced supply of heating and cooling from environmental heat sources and heat sinks offers opportunities to make excess heat from cooling available as a resource for efficient heating. [3, 4]

As a result, developers of residential housing recently turn to a broad implementation of Low Temperature Heating and High Temperature Cooling with embedded water-based systems.

An especially promising technical solution is the combination of thermally activated building systems (TABS), ground heat exchangers and heat pumps in between both systems, widely addressed as GEOTAB-buildings [3].

Low Temperature Heating and High Temperature Cooling is a fully developed and well documented technology, so far dominantly implemented in newly built office and public buildings [5].

Recently the broad implementation of these technologies in the large-scale residential building sector gained momentum. There are some important issues arising at this point of mass application in a new building segment, which are still under discussion among designers, builders, producers and users.

The present paper discusses three key issues, related to the application of combined heating and cooling with embedded water-based systems in newly built multi-storey residential estates:

- Capacity limits of ceiling heating due to comfort aspects.
- Capacity limits of floor cooling due to comfort aspects and condensation risk.
- Energy efficiency and control issues of different types of TABS.

2. Research Methods

Results in the present paper are derived from the following sources:

Post occupancy performance evaluation and user surveys from eight Austrian GEOTABS housing estates: Size from 24 to 335 flats. Location in Vienna and Linz, both Austria. Heating/cooling-components either activated ceilings or floor-heating/cooling. Heat-generation/Heat-removal by monovalent HP/Freecooling or bivalent HP/district-heating/Freecooling. The estates analysed are in operation for 1 to 4 years and evaluations have been carried out by institutions of the authors.

Two-dimensional, static as well as dynamic, heat flux analysis of different types of activated ceilings and floors, embedded in a parametric study on the question of benefits and limitations of different positions of the hydronic pipe systems within the activated concrete ceiling. These calculations have been carried out with Antherm 2D DYN by the institutions of the authors.

Extensive literature review.

3. Capacity limits of ceiling heating due to comfort aspects

It is well known and validated that ceilings offer specific strengths for cooling, while floors offer specific strengths for heating. But for economic as well as technical reasons there’s a strong wish to use one activated element for both services: Either (a) use the floor heating additionally for cooling, or (b) use the ceiling cooling additionally for heating.

The recent trend in multistorey residential buildings goes towards option (b), using thermally activated ceilings, both for cooling and for heating. However, this raises the question about the comfort and capacity limits of such heated ceilings.

It is well documented in scientific literature and international standards that ceiling cooling is significantly efficient and highly comfortable. Regarding capacity and efficiency ceiling cooling benefits from a high value of the total heat exchange coefficient in the range of 11 W/m^2K [6, 7]. Regarding comfort it benefits from mankind’s evolutionary training living under the cold sky, which is the reason behind the low risk of dissatisfacture from temperature asymmetry beneath a cold ceiling [8].

On the contrary, the total heat exchange coefficient of ceiling heating is not higher than 6 W/m^2K. [6, 7] Furthermore, international comfort standards, namely ISO 7730, recommend limiting the temperature asymmetry to a level of $\Delta T_{rad} \leq 4$ K, when targeting a comfort level of category B [8].

The risk of local discomfort from asymmetry of radiant temperature is depicted **Fehler! Verweisquelle konnte nicht gefunden werden.**, according to [8].

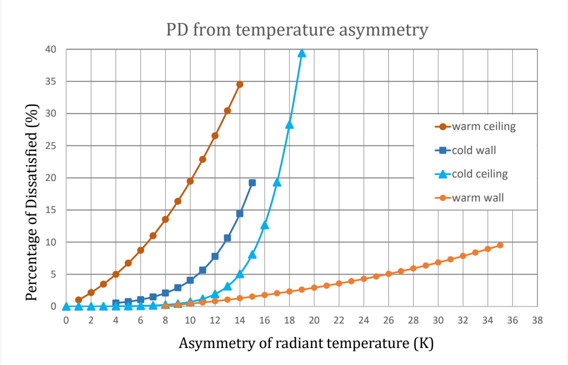

Fig. 1 Local discomfort from cold or warm ceilings & walls

It is this aspect of local discomfort that limits the capacity of heated ceilings. In practice though, observed in many real design processes, the comfort limit of $\Delta T_{rad} \leq 4$ K is repeatedly misunderstood as a limit of the temperature difference between the surface temperature of the ceiling and the room temperature, with again a varying interpretation of “room temperature”. This interpretation leads to a mismatched leads to a limit of heating capacity of (6 W/m^2K * 4 K) = 24 W/m^2.

The correct definition of ΔT_{rad} is the difference between the plane radiant temperature of the two opposite sides of a small plane element, in case of the activated ceiling, of a horizontal plane element [5, 8, 9].

Fig. 2 illustrates qualities that influence the view factor of a ceiling, which are room dimensions, individual position in the room and room height.

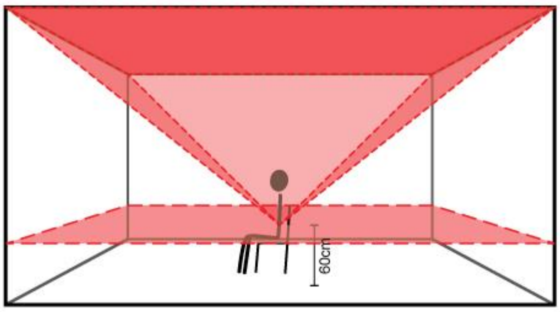

Fig. 2 View factor to an activated ceiling

Based on this correct definition and applied to a big and thus critical 5x6 m room with a height of 3 m, the maximum of the permissible surface temperature of a warm ceiling results in values of around 7 K above the room's operative temperature. This leads to a permissible heating design capacity of ceiling heating of slightly more than 40 W/m^2 [5].

This level of heating design capacity is sufficient for buildings with an up-to-date level of thermal insulation.

Based on qualitative interviews with the tenant service of eight multi-storey residential estates in Austria, complemented by ten further qualitative interviews with tenants, not a single complaint was reported regarding dissatisfaction due to the ceiling heating in general. However, in two flats on the ground floor, adjacent to the underground parking, complaints about thermal discomfort due to the cold floor have been reported. Thus, it is recommendation to backup ceiling heating in such special cases by additional floor heating.

4. Capacity limits of floor cooling due to comfort aspects and condensation risk

Namely in private residential houses, floor heating is still the preferred heating system. Therefore, together with climate change and together with reversible heat pumps, there's a strong tendency to use floor heating supplementary for cooling.

This raises the question about the capacity limits of floor cooling, in respect to comfort aspects as well as condensation risk.

Firstly, there is the risk of local discomfort arising from the thermal contact between the floor and the human body, i.e. the feet. The phenomenon is thoroughly described in the international comfort literature and standardisation [8, 10-12].

ISO 7330:2005 presents a correlation between the floor temperature and the predicted Percentage of Dissatisfied (PD), valid for people wearing light shoes. [8] Under these conditions, an acceptable level of comfort, with PD ≤ 5%, again targeting a comfort level of category B [8] is supported at floor surface temperatures between 19°C and 28°C. (See **Fig. 3**) Additionally, ISO/TS 13732-2:2001, based on original research from B. Olesen, 1977, presents comfortable floor temperature limits for people with bare feet or wearing light socks, for 1' and a 10' occupancy time, depending on the floor material, based on climate-chamber experiments. [11, 12] For the occupancy time of 10', the comfortable floor temperature range is given as 23°C to 28°C for wooden floors and as 26°C to 28,5°C for concrete floors.

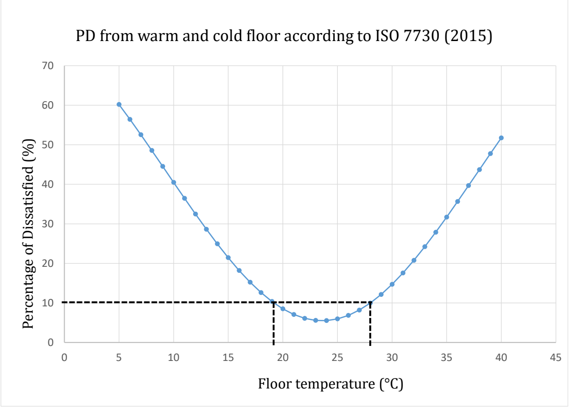

Fig. 3 acceptable range of floor temperature, for people wearing light shoes, according to ISO 7730:2005

Secondly, there is the risk of local discomfort arising from asymmetry of radiant temperature, caused by floor cooling. The influence of the floor's radiant temperature to the asymmetry of the radiant temperature is even more significant than it is from the ceiling, since the view factor from a seated or standing person to the floor is double as high as the view factor to the ceiling. [5] Based on the set of formulars and sources, which has already been discussed for ceiling heating, the surface temperature of a cold floor, again under the boundary conditions of a typical open-plan office, should not be more than 4 K lower than the room's operative temperature.

Thirdly, there is a condensation risk, when applying floor cooling in residential houses. Most flats are not equipped with ventilation systems, especially not with dehumidification systems. Therefore, there is little assurance against an uncontrolled rise of the absolute humidity and respectively of the dewpoint temperature, within the rooms. EN 1264-3 suggests a design dewpoint temperature of 18°C, what equals an absolute humidity of 13 g/kg. [14] Facing climate change, accompanied by longer heatwaves with less nocturnal cooling, the level of summerly humidity is expected to rise in most European cities. The dewpoint risk is exacerbated by the use of wooden floors, which are sensitive not only to condensate but also to mold growth, starting from persistent levels of >70% humidity. Finally, the condensation risk is not only relevant at the floor surface but is most relevant at the boundary layer between the screed and the impact sound insulation: With floor cooling this is the coldest point of the system, exposed to the full level of indoor air vapour pressure.

In summary, floor cooling in residential buildings must be operated with utmost care, to avoid both comfort and condensation risks. As long as it is not supported by active dehumidification, it has to be generally avoided in warm and humid climates. [13] Even in climates with moderate humidity, below 15 g/kg, the water flow temperature should not be lower than 20°C. **Fig. 4** illustrates temperatures and heat flow for this safe setpoint, applied to an exemplary floor construction, made of 1 cm wooden floor on 6 cm of screed on 3 cm of impact sound insulation.

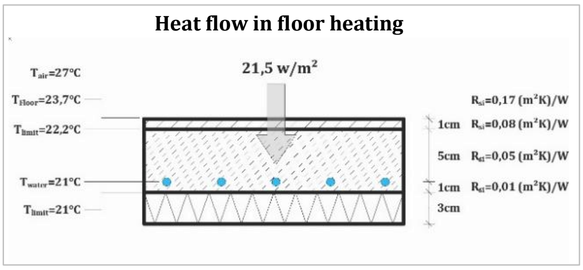

Fig. 4 Temperatures and heat flow in floor cooling and average water temperature of 21 ° C

Under these conditions, the cooling capacity of the floor cooling is limited to a value of approx. 20 W/m² at a room temperature of 27°C.

5. Energy efficiency, energy flexibility and control issues of different types of TABS in residential use

Low temperature heating and high temperature cooling in general, commonly addressed as Low Exergy Systems, TABS especially, are highly regarded as energy efficient. Which they are, in combination with heat generation by heat pumps and with heat extraction by chillers and/or free-cooling. Heat pump SCOPs as well as chiller SEERs benefit from the low temperature differences between process water and environmental heat sources/sinks. Thermal inertia of thermally activated building structures allows a temporal unbundling of heat generation and heat release, opening a wide field of energy flexible applications, maximizing the use of renewable environmental heat sources and heat sinks [15, 16].

The inertia of concrete core activation is a significant strength in terms of utilizing the potentials of energy efficiency and energy flexibility. But it is a challenge finding and applying the right control strategy for the operation of TABS. Again, there is a lot of literature available for the TABS application and control in office buildings, schools, and others.[16, 17] The field application in commercial housing is starting now, raising some new issues and already bringing some new learnings. Selected learnings from own studies and a post occupancy survey are presented here.

5.1 The position of the pipe layer, influencing energy efficiency and energy flexibility

In the application of TABS in residential buildings, the optimal position of the pipe layer within the concrete structure of the ceiling is a persistent point of discussion: The classical position, in the middle of the raw ceiling is claimed being optimal regarding activating the full thermal mass as well as being optimal for keeping the pipes save from later damage from drillers. But there is the strong argument for a pipe position adjacent to the ceiling surface, making repair of damage possible, what it is not the case with pipes between the reinforcement grids.

In own parametric studies, carried out with two-dimensional dynamic heat-flow analysis we investigated three different positions of the pipe layers and found even thermodynamically good reasons to prefer the position of the pipe layer close to the surface. **Fig. 5** illustrates this. It shows the heat distribution in steady operation of three variations of concrete core activated ceilings (CCAC). The variants differ from the position of the pipe layer. For comparison, also a typical floor heating was modelled.

CCAC with pipe layer close to surface	*CCAC with pipe layer at the first reinforcement grid*	*CCAC with pipe layer in the middle of the raw ceiling*	*Floor heating*	
42,3 W/m²	39,0 W/m²	35,1 W/m²	42,3 W/m²	***capacity***
30,8 °C	30,8 °C	30,8 °C	32,8 °C	T_{Fluid}
28,5 °C	28,0 °C	27,4 °C	25,9 °C	$T_{Surface}$
ΔT = 0,8 K	ΔT = 0,15 K	ΔT = 0,01 K	ΔT = 0,18 K	***waviness***

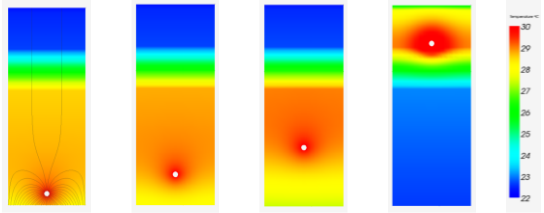

Fig. 5 Temperature distribution and performance indicators of three different variants of concrete core activation and a floor heating system

Learnings from the steady state operation are: Operated with a given flow temperature of 30,8°C and at a room temperature of 22°C, the variant with the pipes close to the surface reaches a surface temperature of 28,4°C and a heating capacity of 42 W/m². Both other variants, operated with the same flow temperature of 30,8°C, show losses in heating capacity up to 17% relative to the first variant. Quite surprising is the result from the floor heating: To reach the same heating capacity as the first variant of CCAC, the floor heating has to be supplied with a fluid temperature of already 32,8°C in stead of 30,8°C in case of the CCAC. This is the effect of the wooden floor, that even overcompensates the better heat flow coefficient of the floor heating.

Further simulation runs investigate the dynamic performance of the CCAC variants. **Fig. 6** illustrates the temperature distribution on a timeline from the left to the right, at steps of 6 hours each. Starting from a constant temperature of 22°C. **Fig. 7** shows a diagram with the temporal development of the heating capacity for the three variants of CCAC in red, green and blue, and with the floor heating on violet. **Fig. 8** shows the corresponding diagram for switching off.

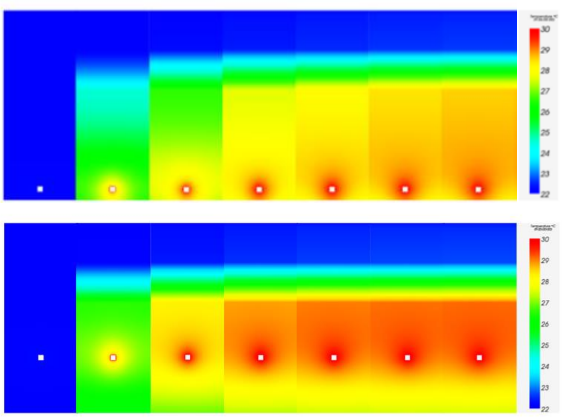

Fig. 6 Timeline of the temperature distribution in two variants of concrete core activated ceilings after switching on, in steps of 6 hours each.

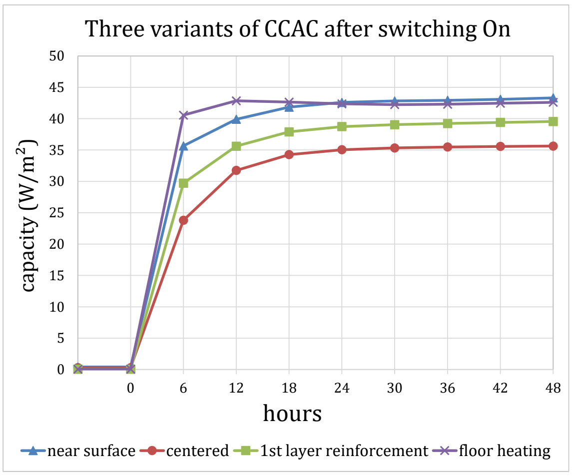

Fig. 7 Temporal development of the heating capacity after switching on: three variants of CCAC in red, green and blue, floor heating in violet.

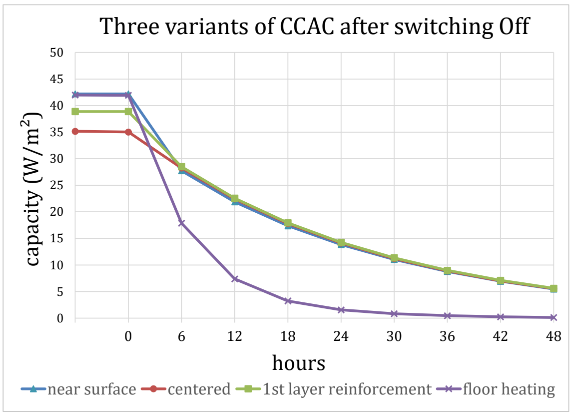

Fig. 8 temporal development of the heating capacity after switching off: three variants of CCAC in red, green and blue, floor heating in violet.

Learnings from the dynamic investigations are: Six hours after switching on, the CCAC variants reach between 70% and 83% of their maximum capacity. Slowest is the variant with the pipe layer in the middle of the raw ceiling. Six hours after switching off, the capacity of all three variants of CCAC drops to the value of 27 W/m² and drops further simultaneously. The mass activation happens for both surface-adjacent and deep position of the pipes.

Against the backdrop of these results, in multi-storey residential applications, we recommend concrete core activated ceilings with the pipe layer close to the ceiling's surface: The mass activation is still existent on a high level, what keeps the possibilities of energy flexibility. The fluid temperatures can be kept closer to the room's temperature, what is good for energy efficiency. And the chance of repair in case of damage is given.

5.2 control strategy

There is a lot of scientific literature dealing with optimized control algorithms for concrete core activated ceilings, including predictive control and others. Only a few of them give answers to the special needs of residential housing, being multiple users without a boss and certain time schedule. People of different needs, culture, age and educational background [17, 18].

Based on results from a post occupancy survey and monitoring in eight housing estates with thermally activated ceilings for both heating and cooling, we give the following recommendations regarding control strategies:

For cooling, full acceptable thermal comfort conditions are expected with permanently running the thermally activated structures through the full period between the heating season with a constant flow temperature of 21°C. This is a very robust strategy, with a good self-regulating effect: If a room's temperature drops, the temperature difference against the ceiling shrinks and cooling stops. If a room's temperature rises, e.g. towards 27°C, the cooling capacity multiples, up to 40 W/m^2. Planners and contractors have learned, to never give guarantees for expected room temperatures. Yet, the survey revealed extraordinarily high levels of satisfaction with this system control strategy. However, complaints came concerning cooled bathrooms. We recommend therefore to exclude the bathroom circuit from cooling. It is thus important to shut down the water circuit in the ceiling of the bathroom during the cooling season.

Developers should indeed not promise certain temperature levels within the room. TABS are a strong improvement of summer comfort, they are though no air conditioning. Furthermore, landlords should not charge the cooling to the tenants. It would be bad for the seasonal efficiency of the system, if building residents started to block the cooling function.

For heating, a very flat heating curve is needed, controlling the flow temperature according to the outside temperature.

Residential spaces should be built in a way not to exceed a design heating load of 40 W/m^2. Zone thermostats proved being good enough. Manually regulating the flow in special circuits proved favourable. Finally, thermostats linked to TABS in residential buildings should be as simple as possible: There should be no options for night reduction and no weekly programs.

In case of heating with concrete core activated ceilings it has to be accepted that temporal, room-by-room temperature adjustment is impossible. In fact, this is no shortcoming, since it is the usual situation during all periods when the flats are in free running mode. Thus, the question arises whether buildings that are heated and cooled exclusively with embedded water-based surface heating and cooling systems may be evaluated according to the adaptive comfort requirements. According to the international standards, the application of the adaptive comfort theory is strictly restricted to buildings without active heating or cooling [20, 21]. In case of embedded water-based surface heating and cooling systems it night be argued that those buildings are perceived as free running buildings. The scientific discussion in this case is still going on [22].

6. Conclusions

Low temperature heating and high temperature cooling with embedded water based surface heating and cooling systems recently enters its broad application – newly – in residential buildings. Those systems enable highly efficient use of heatpumps and freecooling, not least in combination with geothermal environmental heat sources and sinks.

Available results from completed projects and accompanying scientific research confirm the functionality of these systems, also in commercial housing. First conclusions can be drawn, and first experiences and recommendations can be summarised as follows:

For commercial reasons it is necessary to decide either for ceiling heating and cooling or for floor heating and cooling. Both theoretically and practically substantiated, the arguments for using the ceiling predominate. In the discussion about the correct position of the pipes in the ceiling, there are convincing arguments in favour of laying the pipes close to the surface.

In view of the special usage situation in residential buildings, the control of the systems should be very simple and robust. For cooling, excellent experiences are made with permanently running the thermally activated structures with a constant flow temperature of 21°C. For heating, good results are obtained with very simple zone thermostats, without any features of nocturnal temperature reduction or weekly programs.

In practice, the conditioning of residential buildings that are heated and cooled exclusively with embedded water-based surface heating and cooling systems is satisfactory, though individual and room-by-room temperature adjustment is de facto impossible. Based on this, there's an ongoing scientific discussion, whether such buildings may be evaluated according to the adaptive comfort requirements. This would be in contradiction to the international standards, which restrict the application of the adaptive comfort theory to buildings without active heating or cooling. In case of embedded water-based surface heating and cooling systems it might be argued that those buildings are perceived as free running buildings. The scientific discussion in this case is still going on.

7. Acknowledgements

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9. Data Access Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.