LOW EXERGY CEILING HEATING/COOLING SYSTEMS FOR FUTURE BUILDINGS

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SUMMARY
This paper presents data from lab measurements of ceiling heating systems compared to conventional lightweight under-floor heating systems. The measurements show that for the same average water temperature, the total heat flux from ceiling heating systems can be similar or higher compared to conventional lightweight under-floor heating systems. Ceiling heating systems can therefore utilise very low water temperatures for heating purposes. Ceiling-heating systems are easier to install compared to under-floor heating systems, and the whole surface of the ceiling can normally be active as heating or cooling surface, whereas floor heating systems normally have obstructions like carpets and furniture. The larger exposed active surface of the ceiling, and lower thermal resistance between the piped water and the ceiling surface, compensate for the lower convective heat flux from the ceiling. For low or moderate heat demands (20 ~ 40 W/m²), the vertical temperature gradient from 0.1 ~ 1.1 m above floor level for ceiling and under-floor heating, are approximately the same and below 1.0°C. With higher heat demand, we can achieve the same favourable vertical temperature gradient by creating a forced convection (e.g. by placing a ventilation supply diffuser in the ceiling). Ceiling heating systems, mainly based on radiation, will also be heating up the floor surface and for a well insulated floor construction we will have near ideal floor surface temperatures for persons with light indoor footwear. Unlike conventional water-based under-floor heating systems, ceiling heating has low thermal mass, enable it to respond quickly to temperature changes. Ceiling heating systems can also effectively be used for cooling purposes (e.g. in combination with heat pump systems), providing the building with a simple and excellent tool for temperature control. This is absolutely essential for future low energy buildings where overheating can be a serious problem. Ceiling heating/cooling systems are therefore well-suited for future low-energy(exergy) buildings.

1. Introduction
One big challenge for heating systems in future low energy (exergy) buildings is to have satisfactory, energy efficient, indoor temperature control. The main thermal comfort problem, which may occur in well-insulated buildings, is large variations in the room temperature due to changes in internal loads from occupants, lightning, appliances or direct sunlight. Changes in internal loads have therefore a high impact on the room temperature, especially for well-insulated lightweight constructions. Low exergy ceiling heating/cooling systems can be one answer to this challenge.

Ceiling heating is a novel and very interesting solution for low-temperature heating systems in new low-energy buildings. Though the system is primarily intended for heating, it can also effectively be used for cooling. The system has a low thermal mass and responds quickly to temperature changes. Most of the heat is emitted as radiation, the convection component being more limited. Heat emission by radiation will increase the temperature of the other surfaces in the room and thus provide good thermal comfort. The maximum ceiling surface temperature is limited to 30°C, corresponding to a maximum heat flux of about 60 W/m² at a room temperature of 20°C. However, for new low-energy housing with lower heat demand, the ceiling temperature can be considerably lower, with a maximum of about 25~26°C (Figure 1). In Norway, new building codes were introduced in 1997 resulting in an essential improvement of insulation standards, especially floor insulation, which was increased from 60 mm to over 200 mm of EPS insulation. We expect soon a further tightening of the national insulation standards in connection with the EU EPBD, especially the windows, together with improved airtightness and increased use of ventilation heat recovery. The design heat load for new low energy houses can drop to 20 ~ 30 W/m² floor area (Figure 2).
The space heating demand for single-family detached house 138 m². [Oslo climate external design temperature (−20°C)]

The space heating demand for single-family detached house 138 m². [Normal winter day in Oslo, −5°C]

Figure 1. Heat requirement and fluctuation in heat demand for space heating. Well-insulated buildings require an effective temperature control to deal with variations in internal loads from occupants, lightning, appliances and direct sunlight.

This decrease in heating requirement for new well-insulated buildings, and the corresponding drop in ceiling surface temperature for ceiling heating systems, will extensively improve the indoor climate (i.e. reduce radiant temperature asymmetry). It is recommended that a heated ceiling should not provide a radiant temperature asymmetry exceeding 4 – 5°C in enclosures with high standards of indoor climate. Less than 5 % of the population is then predicted to feel uncomfortable due to overhead radiation (Figure 2).

Figure 2. Influence of radiation temperature asymmetry. Percentage displeased.

Forced convection can increase the heat flux from ceiling heating systems. In buildings with balanced ventilation, the ventilation supply air may be used to create such forced convection. Alternatively, a ceiling fan may be used to blow air along the heated ceiling. Such fans will only be needed for short periods, for instance during quick heating up periods, or when the outdoor temperature is very low. It is quite the opposite when the ceiling is used for cooling. Although the convective heat flux from a cold ceiling could be compared with a hot floor, forced convection from the ventilation supply air or a fan will increase the cooling flux from the ceiling.

The whole surface of the ceiling will be active as a heating or cooling surface. For under-floor heating systems, in comparison, parts of the floor will normally be covered with carpets or furniture, reducing the total heat being emitted. The exposed surface actively emitting heat will therefore normally be larger for ceiling heating than for under-floor heating. Moreover, the same strict load-bearing and functional requirements do not apply for materials used in the ceiling, as they do for materials used in the floor, so thinner materials may be used in the ceiling than in the floor. The thermal resistance between the pipes and the ceiling surface will therefore be less than for a typical lightweight under-floor heating system. The temperature of the heated surface has to be about 1.0°C higher for ceiling heating than for under-floor-heating, to emit 30 W/m², due to the difference in convective heat transfer coefficient.
In summary, the larger exposed surface of the ceiling, and the lower temperature drop between the water in the pipes and the ceiling surface will approximately compensate for the lower convective heat transfer coefficient at the ceiling. Using the same water temperature in the pipes, the total heat flux from ceiling heating will be similar or higher to that of under-floor heating. Ceiling heating systems in intermediate suspended floors in particular, have high efficiency and low additional heat losses (such as thermal bridging at the ground floor perimeter). Ceiling heating systems also have a number of practical advantages over under-floor heating, such as being well protected against mechanical damage. Ceiling heating systems are also easier to install than under-floor heating systems.

Special qualities for ceiling heating/cooling systems installed in low energy buildings

- Whole ceiling active as heating or cooling surface
- Low thermal resistance between pipes and ceiling surface
- Low thermal inertia
- Good temperature control (heating and cooling)
- Uneven surface temperature will not affect indoor climate
- Highly efficient in combination with ventilation
- Low additional heat losses (intermediate suspended floor/ceiling)
- Simple installation in combination with airborne sound attenuation
- No restrictions for floor materials (floor heating)

2. Experimental installation

The ceiling heating/cooling and floor heating system in the test room (calorimeter type) both have a heated area of 13 m². Both systems are lightweight alternatives with 0.5 mm aluminium sheets glued to porous fibreboards (Figure 3). The same prefabricated heat distribution system can be used for floor, wall an ceiling heating systems. Further description of the test room in detail is given in [1].

3. Experimental results

3.1 Heat flux

Figure 4 shows measurements of heat flux from under-floor and ceiling heating. The measured heat flux from the under-floor heating system is approximately 10% lower than nominal values presented in the calculation standard EN 1264.
Figure 4. Heat flux from the under-floor and ceiling heating systems versus temperature diff. between the heating surface and an average operative room temperature (natural convection).

Figure 5 shows measured values for the heat emission from the tested under-floor and ceiling heating systems. The load-bearing and functional requirements of materials used in the ceiling are not as strict as those for the under-floor system. Thus, since thinner materials may be used in the ceiling system, the thermal resistance between the pipes and the ceiling surface will be lower than for under-floor heating systems. Ceiling heating can, for instance, be easily integrated into a lightweight airborne-sound insulated, suspended intermediate floor. Due to lower heat resistance for the gypsum board between the pipes and the ceiling surface, the heat emission is the same versus average water temperature for the tested under-floor and ceiling heating systems. By reducing the thickness of the gypsum board from 13 mm to 6 mm we can further increase the heat flux from the ceiling heating system with 20 % for any given water temperature.

Figure 5. Heat flux from under-floor and ceiling heating systems versus average water temperature, (natural convection). Room reference temperature 20°C.

Forced convection can increase the heat flux from the ceiling heating system. In buildings with balanced ventilation, the ventilation supply air may be used to create such forced convection (Figure 4). This combination is very effective to preheat the ventilation air and prevent cold draft during the heating season.
Figure 6. Heat flux from floor and ceiling heating systems versus average water temperature with and without office ventilation (4 h⁻¹). Room temperature 20°C

3.2 Vertical temperature gradient

Figure 7 shows the vertical temperature gradient in the test room with under-floor or ceiling heating. The mean water temperature is 30°C and the heat flux from the under-floor and ceiling heating system is based on radiation and natural convection with no ventilation. The outside reference temperature for the room envelope (floor, walls and ceiling) is –5°C. The envelope has 200 mm mineral insulation. The operative temperature 1.6 m above the floor surface is the same for both systems. The operative temperature was measured at heights 0.6 m, 1.1 m and 1.6 m above the floor, and differ by only 0.1°C with the corresponding dry bulb air temperature. The heat flux from the ceiling heating system is slightly higher than for the under-floor heating system. In the test room the floor area is only 13 m², which is 27 % of the total floor/wall area, which is approximately the same percentage of radiant heat that the floor received from the ceiling heating system. A room with larger floor area will accordingly receive a larger percentage of the radiant heat from the ceiling. With a floor/ceiling area of 40 m², the radiant heat emission from the ceiling received by the floor area is increased to about 40 %.

It is interesting to note, in Figure 7, that the radiant heat emission from the ceiling heating system fully compensates for the heat loss from the floor, and even to some degree increases the floor temperature. Under steady-state conditions the convective heat flux from the floor surface is limited to 2 ~ 3 % of the total heat flux from the ceiling heating system. However, during the heating-up period, the convective heat flux from the floor surface will be much higher. Normally for a slab-on-ground, the average soil temperature just below the floor insulation is 6 ~ 12°C in Oslo climate. This will, in this test, reduce the heat loss from the floor surface to the soil by about 67 %. Consequently, with the same water temperature, the air temperature will significantly increase and the radiation temperature asymmetry decrease. This emphasizes the benefit of having good floor insulation together with a ceiling heating system. Thermal comfort depends on a well-insulated floor.

Figure 7. Floor or ceiling heating. Vertical air temperature gradient. Natural convection with no ventilation. Mean water temperature 30°C. Heat flux from the floor and ceiling heating system: 24.1 W/m² and 24.5 W/m². Reference temperature is –5°C.
Figure 8 shows the vertical temperature gradient in the test room with a ventilation of 1 air change/hour. Inlet temperature for the ventilation air is 18°C from the radial air diffuser located in the middle of the ceiling.

**Figure 8.** Vertical air temperature gradient with floor or ceiling heating. Ventilation rate 1 air change/hour. Inlet air temperature 18°C and water temperature 30°C. Heat flux from the floor and ceiling heating system: 20.0 W/m² and 20.6 W/m². Reference temperature 5°C.

Figure 9 shows the vertical temperature gradient in the test room with ventilation rate 4 air changes/hour (office ventilation). The outside reference temperature is –5°C, water temperature 30°C, and the inlet temperature of the ventilation air is 18°C. The vertical temperature gradient for the floor and ceiling heating systems is practically the same, but the heat emission from the ceiling heating system is 10% higher than for the under-floor heating system.

**Figure 9.** Vertical air temperature gradient with floor or ceiling heating. Ventilation rate 4 air changes/hour (office ventilation). Inlet air temperature 18°C and water temperature 30°C. Heat flux from the floor and ceiling heating system: 26.6 W/m² and 29.3 W/m². Reference temperature –5°C.

### 3.3 Heat emission during a heating up period

In figures 10 & 11 we can see that the ceiling heating system has low thermal mass, enabling it to respond quickly under the heating up period. The starting temperature in the test room is about 5 ~ 6°C.

**Figure 10.** Lightweight floor and ceiling heating systems (natural convection). Heat emission during a heating up period.
3.4 Ceiling cooling

Figure 12 shows some test results for the actual floor heating system and the ceiling heating/cooling system. The heat flux from the floor and ceiling heating/cooling system is presented as a function of temperature difference between the heating/cooling areas and mean operative room temperature. Not surprisingly, the overall heat transfer coefficient for the floor heating and ceiling cooling system is of same magnitude. With 3°C temperature difference between mean operative temperature and heating/cooling floor or ceiling area, the overall heat transfer coefficient is approximately 9 W/m²K. With an average room temperature of 25°C and water temperature of 13°C, the cooling flux from the tested ceiling cooling system is about 35 W/m². This is normally sufficient cooling capacity for a room with direct sunlight with an efficient solar shading system. Because of a more effective convective heat transfer coefficient from the actual ceiling heating system, the test result for the cooling flux was expected to be somewhat higher. This may due to the fact that we did not reach steady state condition or had some unintentional ventilation heat loss from the test room. However, by reducing the gypsum board from 13 to 6 mm we can improve the cooling efficiency by about 20%. The cooling capacity from the ceiling cooling system can also be improved by forced convection.
4. Conclusion

Low-temperature ceiling heating systems can be an attractive solution for future well-insulated buildings. The tested ceiling heating system is primarily developed for heating purposes, but may also effectively be used for cooling. The radiant heat component is similar in magnitude to that of under-floor heating systems, whereas the natural convective component will be lower for ceiling heating systems. For a given temperature difference between the heated surface and operative room temperature, the heat flux from the floor heating system is 20 ~ 25% higher than for the ceiling heating system. This difference in heat flux can be compensated with a higher ceiling surface temperature, which does not necessarily require a higher water temperature. One important design feature for all lightweight low temperature heating systems is to keep the temperature difference between the water temperature and heated surface as small as possible. The load-bearing and functional requirements of materials used in the ceiling are not as strict as those for the under-floor system. Thus, since thinner materials may be used in the ceiling system, the thermal resistance between the pipes and the ceiling surface can be lower than for an under-floor heating system. This can compensate for the lower convective heat transfer coefficient at the ceiling, in which case the thermal efficiency of ceiling heating systems can be at least as good as under-floor systems.

Moreover, the total heat flux from the ceiling can also be increased by means of forced convection. Consequently, with effective ventilation, ceiling heating systems can for a given water temperature have the same, or even higher, heat flux compared to under-floor heating systems. In buildings with balanced ventilation, the ventilation supply air can be utilized to create such forced convection, by locating a radial supply diffuser centrally in the ceiling. Ceiling heating can, for instance, be easily integrated into a lightweight airborne-sound insulated, suspended intermediate floor. Unlike conventional water-based under-floor heating systems, ceiling heating/cooling systems can have low thermal mass, enabling it to respond quickly to temperature changes. Ceiling heating/cooling systems should therefore have a better controllability and ideally be more energy/exergy efficient for future well-insulated buildings, especially in combination with new exergy-saving technologies, such as heat pumps, co-generation or renewable energy directly from solar radiation or from the ground.

5. References
