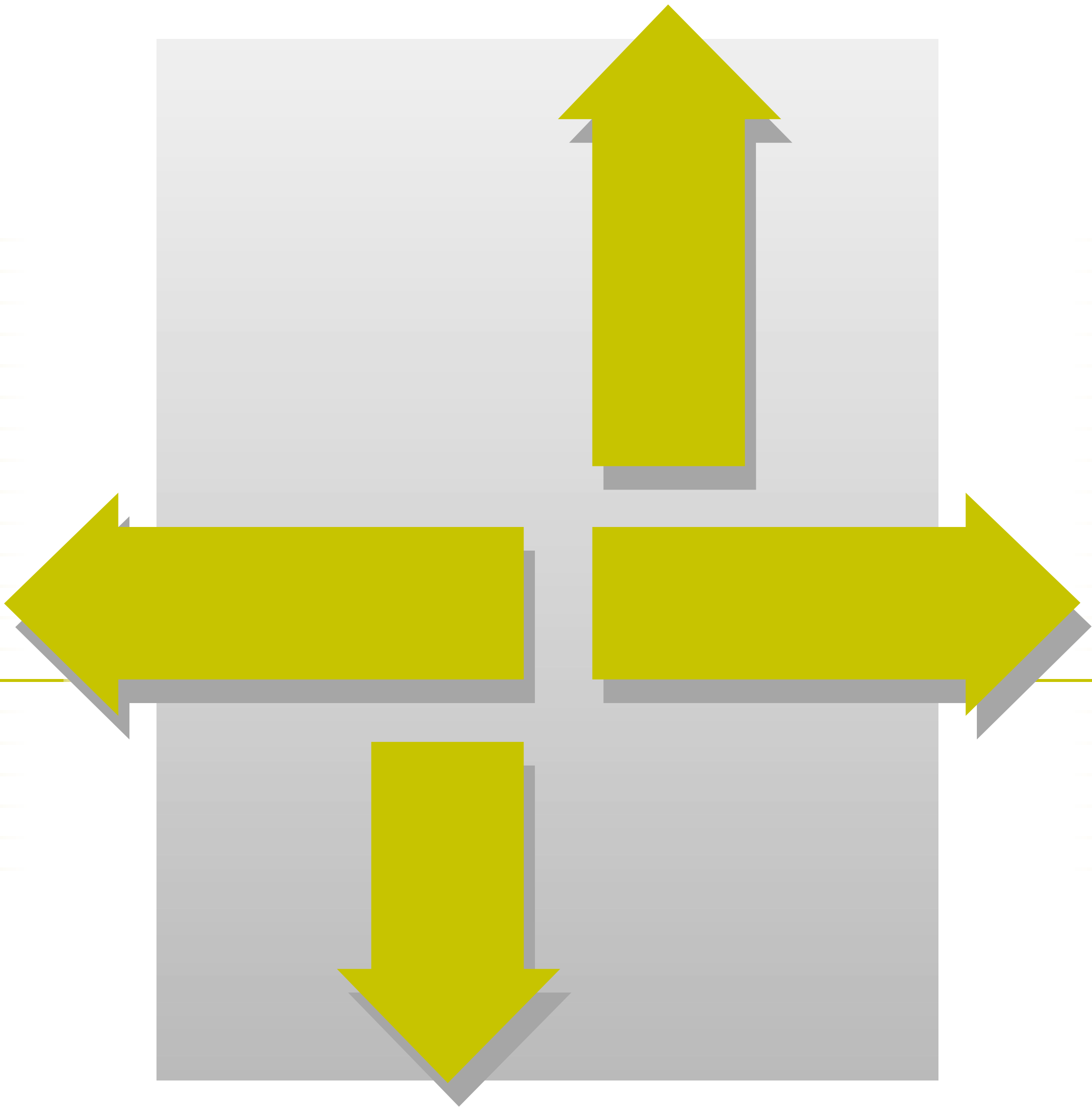
2

Cooling and heating systems

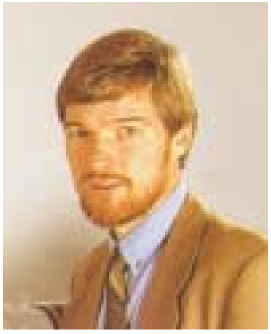
Heating and cooling with ceilings



Technical Report

Heating and cooling with ceilings

Jürgen Nickel*



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Thermally active ceilings for room cooling (cooling ceilings) have been in successful use for years. With these mostly water-cooled systems high cooling loads can be removed economically and a high degree of thermal comfort achieved. A question of growing interest is whether these water-carrying systems can be used for heating.

This paper describes the two functions, heating and cooling, with respect to thermal comfort, layout and application limits.

The original misgivings towards water piping in ceilings directly above the workplace, with attendant fears of possible leakage, condensation, unpleasant coldness, etc. have generally given way to a high level of acceptance. Today, there is a widespread interest in extending the range of application to heating, in order to save on investment costs on the one hand and on the other to dispense with static heaters under or in front of glass facades, which are often undesirable for architectural reasons.

We should recall, however, that already decades ago radiant heating from the ceiling was quite common, but due to user dissatisfaction it largely disappeared from the market, apart from industrial applications. Unlike cooling, heating can quickly exceed comfort limits.

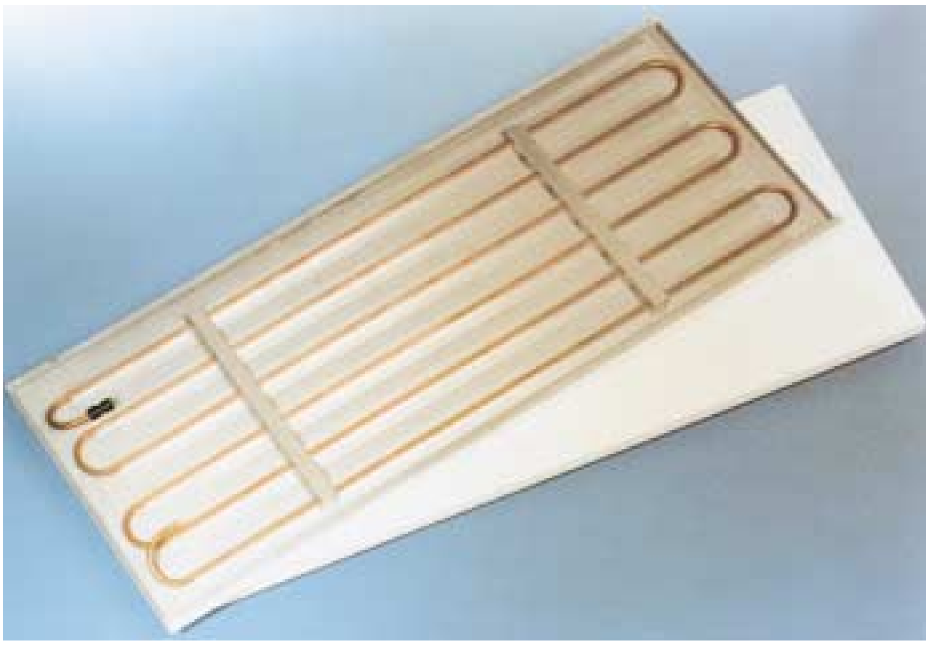
Cooling function

When specifying the layout of active ceiling systems for room cooling, the prime concern is almost always the maximum removable cooling load, while thermal comfort is practically always assured, as years of practice have now confirmed. Decisive for cooling capacity is the flow temperature, which has a minimum limit, due to the condensation risk.

Generally, cooling ceiling operation is designed to prevent condensation of indoor air at any point in the system. Due to the usual outside and indoor air conditions cooling ceilings are therefore mostly run at minimum flow temperatures of 15°C to 16°C. Mean ceiling surface temperatures are accordingly about 17°C to 19°C and are experienced as pleasant by occupants.

The permissible limit values to DIN 1946, P. 2 for the asymmetric radiation of a cooling ceiling are also always maintained.

Due to natural thermal convective flow in cooling ceiling operation a very even air temperature distribution forms in the room with normal minimum fluctuations of under ± 0.5 K over the entire room height.



1

Figure 1: KKS radiant cooling ceiling
Figure 2: SKS convective cooling ceiling

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Laboratory measurements and practical experience have shown that indoor air velocities are extremely low when cooling ceilings are used. With radiant cooling ceilings *(Fig. 1)* with a maximum cooling capacity of about 100 W/m² of active area, the velocities due to natural convective flow are in the range of 0.1 m/s. At capacities around 150 W/m², which can generally only be achieved by convective cooling ceilings *(Fig. 2)*, maximum indoor air velocities amount to about 0.15 m/s.

When mechanical ventilation with ceiling air outlets is used, the indoor air velocities are determined by the respective air distribution system, where the influence of the cooling ceiling is then extremely low.

Generally speaking, the usual applications of cooling ceilings will cause no problems with thermal comfort. Crucial for the layout is cooling capacity, which cannot be raised infinitely after installation due to the dew-point problem on the one hand and the cost of refrigeration on the other. Exact information on the capacity characteristic for cooling ceilings is therefore very important.

Heating function

When thermal active ceiling systems are used for heating, other parameters play a more important role than those for cooling. With respect to their capacity for example it is generally easy to increase heating capacity by raising flow temperature (generally between 30°C and 40°C), without major changes or problems occurring, as happens when cooling, e.g. temperature falling below dew-point. Raising flow temperature also has an insignificant effect only on the economical efficiency of the overall system (in contrast to cooling).

In heating, however, the influences on thermal comfort must be tested very carefully. When heating with ceiling systems, there are 3 criteria that have to be observed for proper operation:

1) Vertical temperature stratification in the room

2) Radiant temperature asymmetry due to the warm ceiling and cold facade

3) Cold air drop at the cold facade resulting in draughts.

When heating from the ceiling a temperature stratification forms in the room as a consequence of the heating output brought in the room. Depending on what additional air distribution system is available, this stratification is more or less heavily influenced by the ventilation. Since the largest heating requirements are when the building is hardly occupied or empty (at night, weekend) and the ventilation plant is running at reduced operation or has been switched off, we shall look in the following at the case without ventilation, where the most pronounced stratification occurs. These statements also largely apply for the use of displacement ventilation systems that are unable to diminish stratification caused by heating.

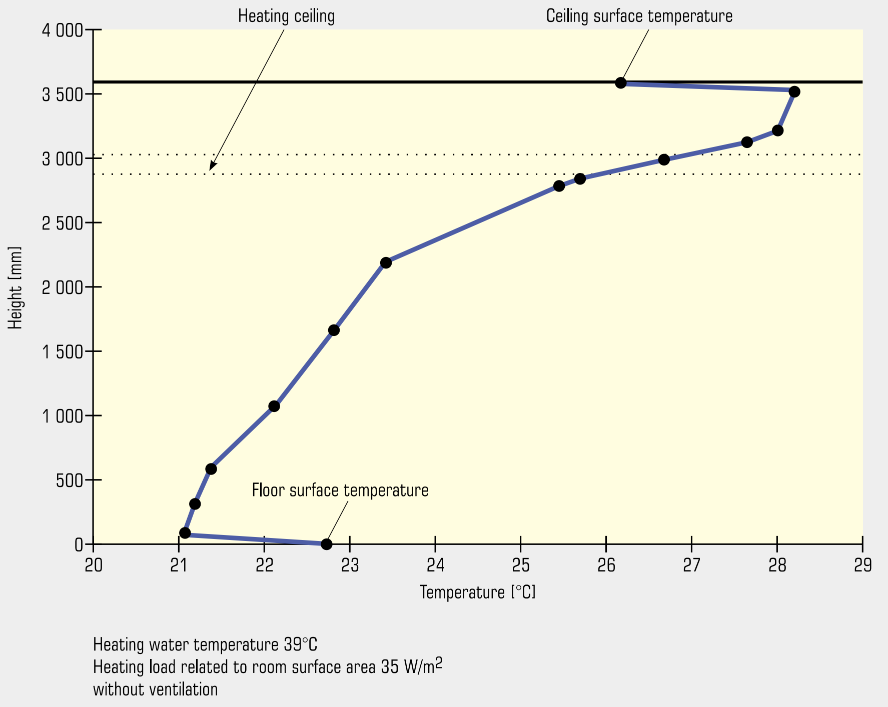
Fig. 3 shows a typical temperature stratification in the room which arises when heating with a convective ceiling. We can see the air temperature stratification from 21°C just above the floor to 26°C just beneath the heating ceiling.

Fig. 4 shows the air temperature stratification in the room (here the difference in air temperature just below the heating ceiling at $\vartheta_{2.5\,m}$

and just above the floor at $\vartheta_{0.1\,m}$) correlated with heating output in the room in relation to surface area. In the tests the active area segment was varied between 12%, 24% and 48%; the heating capacities related to active heating surface ranged between 100 and 350 W/m². The measured values indicate a clear almost linear correlation between temperature difference and heating capacity.

Accounting for the limit value to DIN 1946/Part 2 for a vertical temperature rise of 2 K/m with a clearance room height of approximately 3 m, the maximum temperature difference of the air between floor and ceiling amounts to approximately 6 K, which according to these measurements occurs at a heating capacity of 50 W/m². We may assume that also with varying room heights similar temperatures occur just above the floor or just under the ceiling and that the temperature gradient alters accordingly.

This result shows that heating with active ceiling elements under strict compliance with comfort criteria to DIN 1946/Part 2 is only possible in cases of restricted heat requirement (≤ 50 W/m²). In most cases, the ventilation requirements at free ventilation for the outside air volume flow rates needed for office buildings cannot be met by a heating ceiling complying with comfort criteria.



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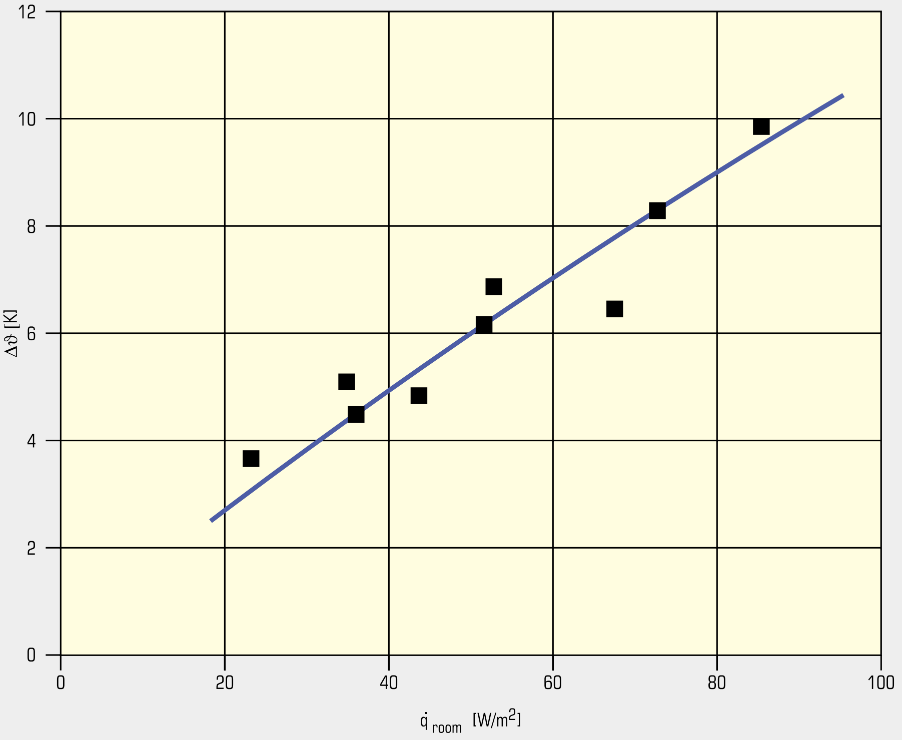


4

Figure 3: Diagram of a typical temperature stratification that forms when heating with a convective ceiling

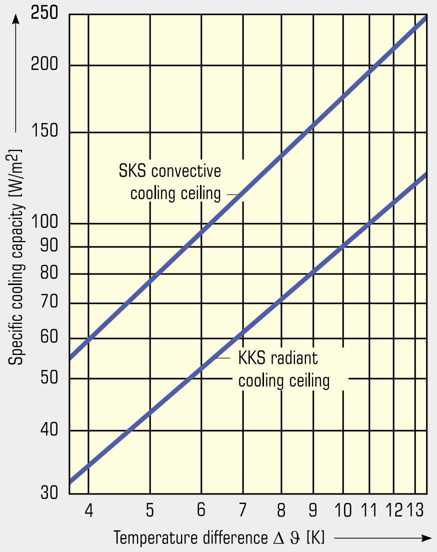
Figure 4: Air temperature stratification in the room (here the difference of the air temperature just beneath the heating ceiling of $\vartheta_{2.5\,m}$ and just above the floor of $\vartheta_{0.1\,m}$) correlated with the heating output in the room related to area

Heat transfer and capacity specifications for heating and cooling

Both when heating and cooling the energy transfer of the ceiling elements to the room is effected in equal amounts via radiation and convection. To be able to make exact capacity specifications the relevant room-side reference temperature for the respective heat transfer mechanism must be indicated. For convection, this would be the air temperature in ceiling proximity, for radiation the mean surface temperature of the areas enclosing the room (wall, floor) and possible items of furniture or equipment accounting for angle factors. Due to the disparate geometries and the unknown temperature distributions, it would seem practically impossible to determine this reference temperature precisely. In addition, a direct distinction by measuring cannot be made between heat transfer by radiation and convection, so that it is impossible to assign the heat load transferred with reference to various temperatures or differences.

As when cooling practically no air temperature stratification forms in the room, defining a room-side reference temperature is very much easier. It has been established that the globe temperature measured in the centre of the room at a height of 1.1 m (approximately mean average value from the air temperature and the mean radiant temperature) represents a very good reference temperature for the room, from which easily replicable capacity specifications related to temperature difference can be obtained. This is therefore also the method applied in compliance with DIN 4715 for capacity measurement at cooling ceilings. *Fig. 5* shows the cooling capacity characteristics for a radiant ceiling system (KKS) and a convective system (SKS), respectively.

Both in heating and cooling operation, the radiation quota in the globe temperature (mean radiant temperature of surfaces measured by the globe thermometer) is a useful reference quantity for heat transmission through radiation. The air temperature included in globe temperature at a height of 1.1 m, however, only represents a good reference temperature for convection when cooling. When heating the difference of air temperatures at this height and in ceiling proximity (air temperature in ceiling proximity determines the convective heat transfer) is very much larger and depends on the total heat load in the room (cf. Fig. 4). Depending on the total

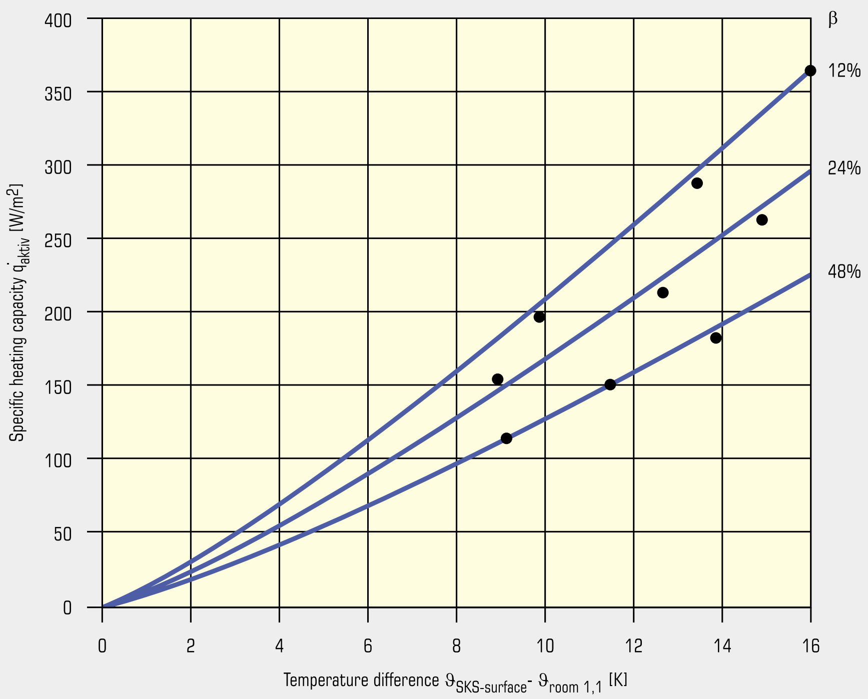


Temperature difference $\Delta\vartheta = \dfrac{\vartheta_{return} - \vartheta_{flow}}{\ln \dfrac{\vartheta_{return} - \vartheta_{flow}}{\vartheta_{room} - \vartheta_{flow}}}$

5

Figure 5: Standard characteristic for cooling ceilings to DIN 4715/Part 1

Figure 6: If the globe temperature at a height of 1.1 m is chosen as a reference temperature analogous to cooling, depending on the active ceiling ratio β we obtain under apparently the same parameters different specific heating capacities



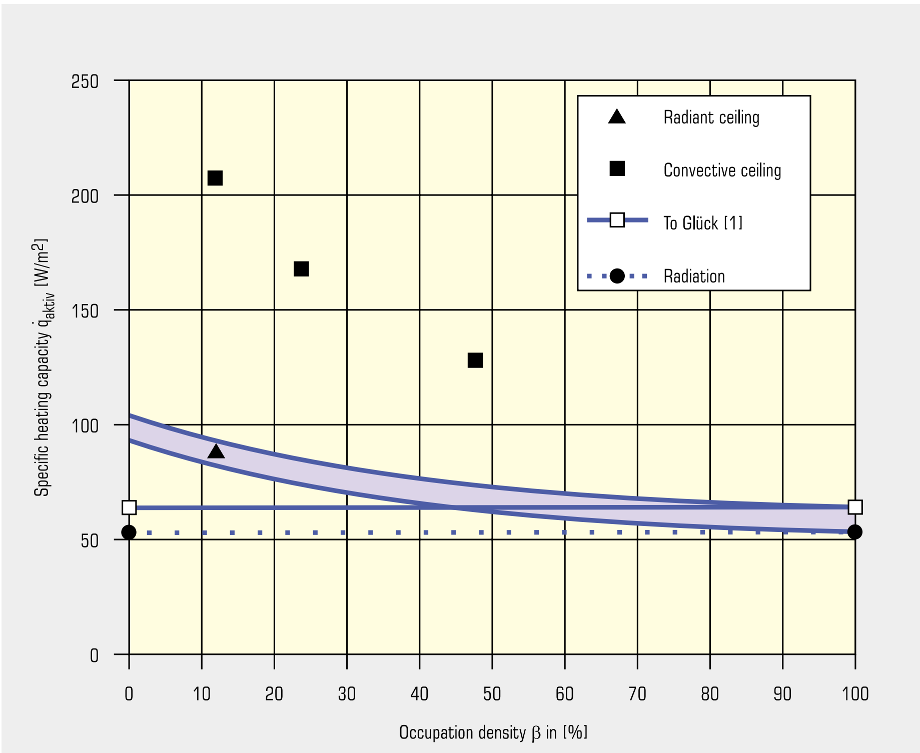
6

load in the room at the same globe temperatures in ceiling proximity, this can result in various air temperatures and thus various convective capacities, which is not accounted for in globe temperature.

If we choose the globe temperature at a height of 1.1 m as a reference temperature analogous to cooling, depending on the active ceiling fraction (share of active ceiling segment in the overall surface) we obtain under apparently the same parameters (same surface temperature and same globe temperature at 1.1 m height) different specific heating capacities, as shown in *Fig. 6.*

We can see a strong correlation of heat output at the same temperature difference with active ceiling ratio (here 12%, 24%, 48%). The reason for the dependence of capacity on active ceiling ratio are the increasing vertical temperature gradients in the room. At higher active ceiling ratio, total heating capacity rises in the room and consequently *(see Fig. 4)* the temperature stratification, so that as a result of the higher air temperature in the ceiling zone the convective capacity quota drops sharply.

In the extreme case with 100% active segment, a practically static warm air cushion could form just under the ceiling, so that the convective quota of the output practically disappears and only radiation emission takes place to the floor, facade and other surfaces. At 10 K temperature difference the total output would then be reduced to a minimum value of approximately 54 W/m² (pure radiation emission as in Glück [1]). This is represented in *Fig. 7* by the dotted line. This figure also shows the above-mentioned test results as well as the capacity of a heating ceiling with $h_{total} \approx 7$ W/m² specified by Glück [1]. While the two theoretical approaches (for the radiation quota as well as the Glück approach [1]) take no account of a correlation to active ceiling ratio, the measurement results reveal a clear dependence, as mentioned. For a closed radiant heating ceiling, therefore, a range of specific heating capacity is specified in correlation with active ceiling ratio as an approximation. More tests need to be made on this correlation, however. Perhaps it is just this dependence that explains why different measurement results (or manufacturer's specifications) on heating capacity vary so much and in some cases why amazingly high figures are specified which cannot be explained in theory.



7

Figure 7: Dependence of specific heating capacity on occupation density

Radiant temperatures and assymmetries

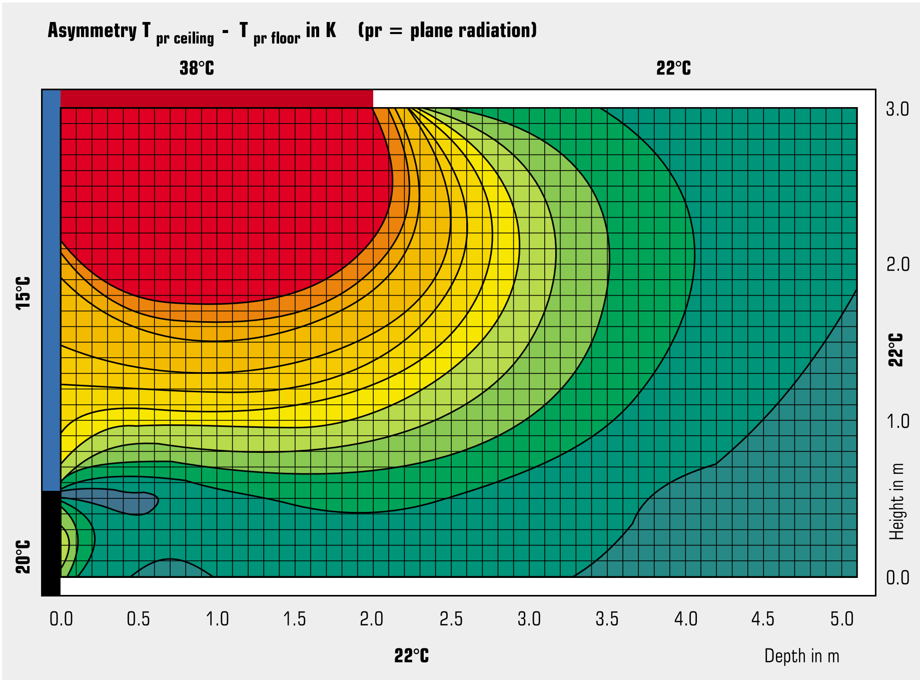
The task of room heating is not only to provide the room with the necessary heating capacity to reach a corresponding air temperature; it must also cater for comfortable radiant temperature conditions. On the one hand, suitably warm surfaces near the facade are supposed to offset the uncomfortable 'cold emission' from the window and on the other the heating should not result in unpleasant heat radiation on the occupants. In addition, the operative temperature (= felt temperature) should not vary too much, which is possible with wide surface temperature differences. In general, a conventional placement of heaters in the parapet of the facades performs these tasks very well, because the radiation effects are equalized due to the immediate proximity of the cold surface (windows) and the warm surface (heaters).

Various experiments show that when using heating ceilings, the best conditions can be obtained by using ceiling strips only about 1 to 2 m broad at the facade with somewhat higher temperatures (compared with large-surface installation covering the whole room).

To evaluate the radiation conditions to DIN 1946, P. 2, the difference of half-room radiant temperatures in relation to a perpendicular plane parallel to the façade (evaluation of 'cold emission' of window) or parallel to the ceiling (evaluation of the warm ceiling) has to be determined. For cold wall surfaces (facades), a limit value of 8 K applies and for the warm ceiling, 3.5 K.

As with today's heat protection panes the inner surface temperatures are practically always over 14°C, the requirements for the cold wall surface ($\Delta\vartheta_{asymmetry} \leq 8$ K) are usually met.

Of critical importance is the effect of the warm ceiling. For a 5 m-deep room (6 m wide) and a heat requirement of 50 W/m², *Figs. 8 and 9* represent the asymmetric radiation at every point on a vertical cutting plane through the room. In *Fig. 8* the heating capacity is provided via a 2 m wide heating strip at a surface temperature of 38°C (h_{total} = 7.8 W/m²K) and in *Fig. 9* via a 4 m wide heating ceiling at a surface temperature of 31°C (h_{total} = 7 W/m²K).



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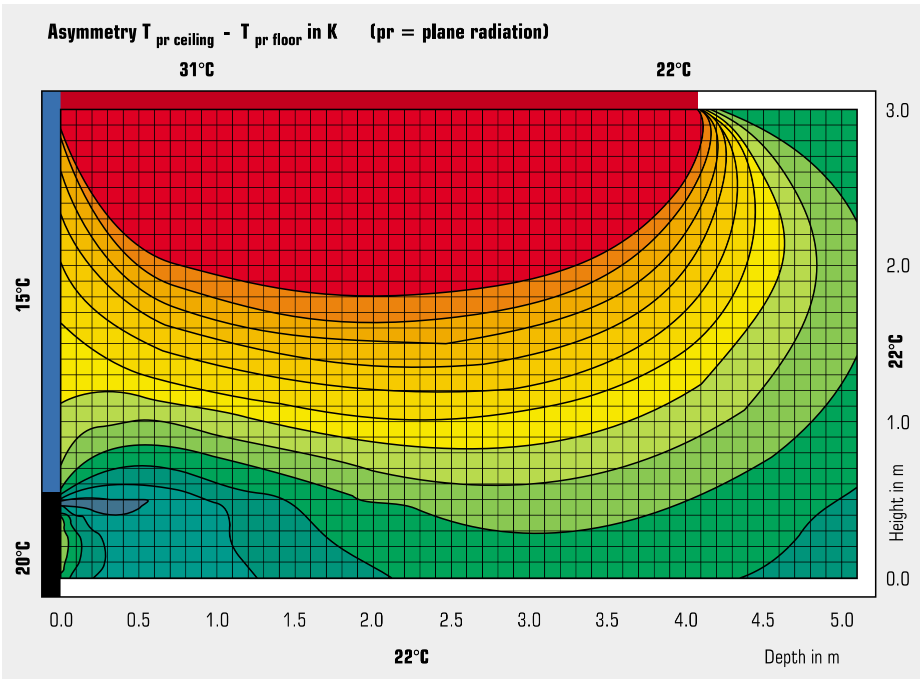

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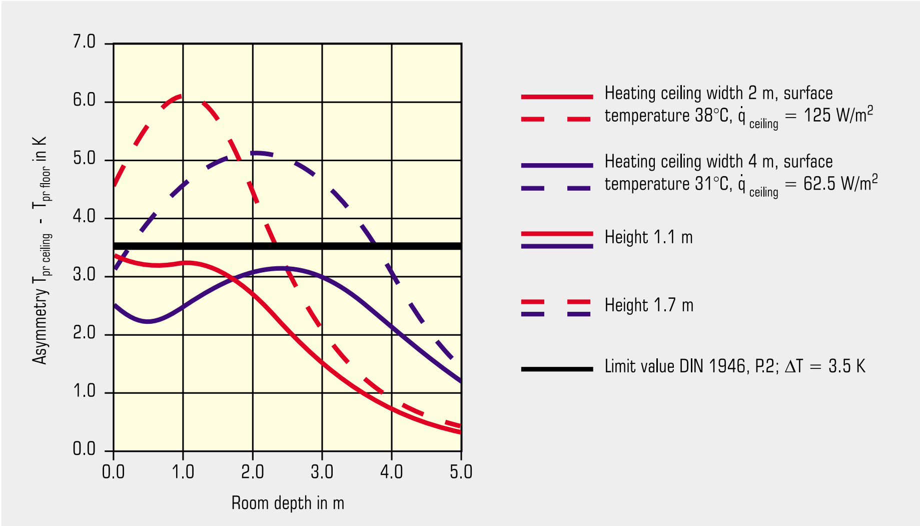
Key to 8 + 9

Figure 8: Heating ceiling strips at the facade
Figure 9: Large-surface heating ceiling

For the room height of 1.1 m (head height of seated persons) and 1.7 m (standing persons) the results are also shown in *Fig. 10*. We can see that with large-surface heating ceilings in a larger area the permissible limit of 3.5 K is exceeded. However, in both cases at the relevant height of 1.1 m for offices, the asymmetric radiation is below the permissible limit. This example shows that by using ceiling heating at a heat requirement of 50 W/m² the permissible limits can only be kept to a seated height. At even higher capacities, the limit would be exceeded here too.

Fig. 11 shows the distribution of the mean radiant temperature with a 2 m wide heating strip. In the occupied zone (up to a height of 1.8 m) the mean radiant temperature ranges between 21.5 and 23.5°C, so that at an air temperature of 22°C the operative temperature is very even in the range of 21.8 to 22.7°C.



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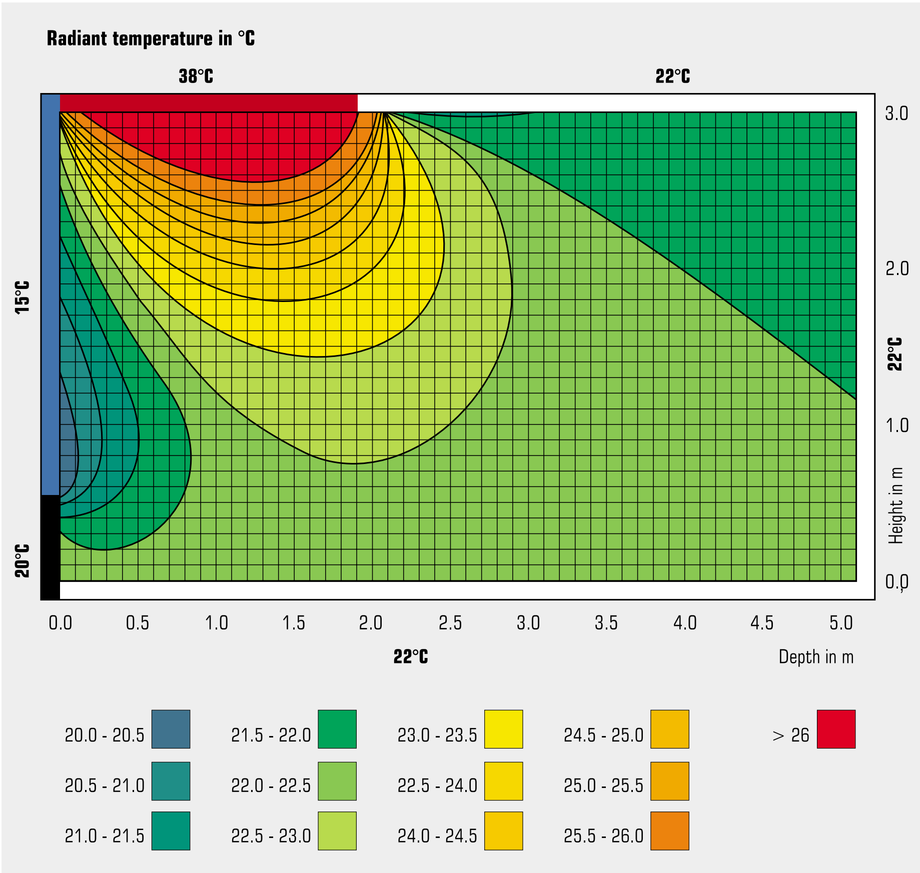


11

Figure 10: Radiant temperature asymmetry at a height of 1.1 m and 1.7 m with $\dot{q}_{room}$ = 50 W/m²
Figure 11: Heating ceiling strips at the facade

Cold air drop

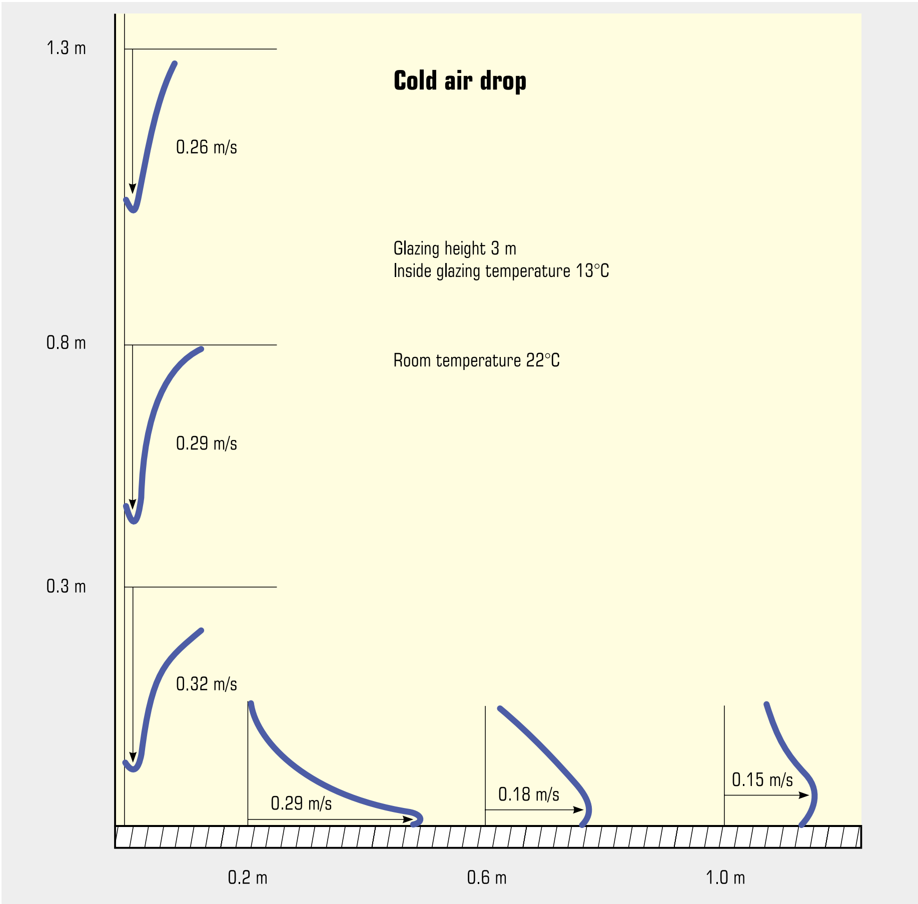
The cold air drop at high glass facades poses a large problem with respect to thermal comfort. The cold air drop can be effectively counteracted by convective heaters or window air curtains at the facades. Heating ceilings, however, have no direct effect on this cold air drop and can only mitigate this problem indirectly by slightly increasing the inner surface temperature in the ceiling zone of the facades.

Fig. 12 shows the problem of cold air drop. The layer of the cold air drop at the facade is only some centimetres thick, but accelerating air downflow is deflected at the floor and thus reaches the occupied zone of the room, where it can cause draught. The maximum velocities of the air flow in the floor zone are lower than at the vertical facade, but the layer gets thicker. Measurements have shown that at distances more than 0.7 m up to 1 m maximum velocities can occur at the critical height of 0.1 m (or above) and must therefore be taken into account in the comfort rating.

The magnitude of the cold air drop depends on the temperature difference between the indoor air and the interior glazing surface temperature, which in turn depends on the outside temperature and the U-value of the window.

Maximum velocities in the layer close to the floor after deflection of the cold air drop can be calculated in close approximation to Heisselberg [2] and are shown in *Fig. 13* for a distance of 1 m to the facade. When assessing thermal comfort account must also be taken of the relatively low temperature of the deflected air from the cold air drop flowing into the room, so that a maximum velocity of u_{max} = 0.17 m/s may not be exceeded.

At this value the requirements of DIN 1946/ Part 2 are also met with low turbulence flow (Tu < 20%). For a predefined window height, the necessary U-value can therefore be determined from the graph at which the cold air drop does not result in indoor air velocities > 0.17 m/s at 1 m spacing. For 3 m window height, we therefore obtain for example U ≤ 1.3 W/(m² · K), for 1.5 m, approximately U ≤ 1.8 W/(m² · K).



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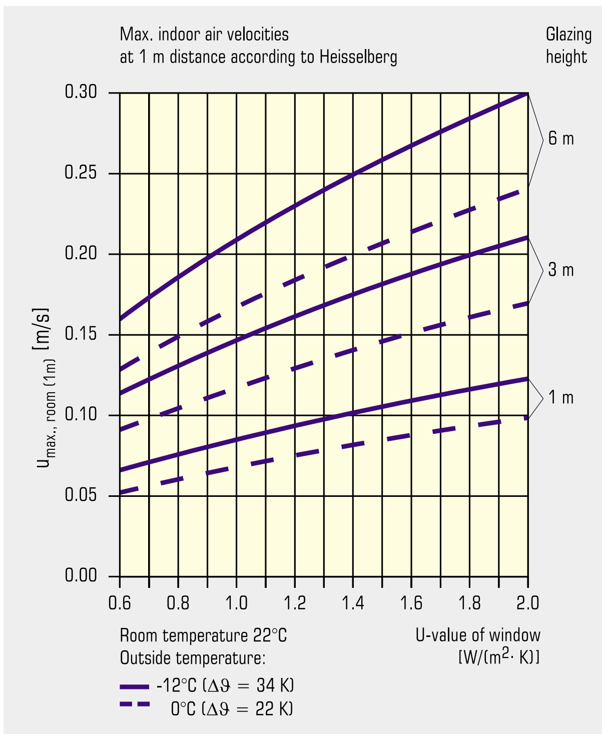


13

Figure 12: Cold air drop at facades
Figure 13: Indoor air velocities due to cold air drop

Summary

Active ceiling systems normally used for cooling as cooling ceilings can also be used for heating purposes where required. To meet the comfort requirements, however, various parameters have to be met.

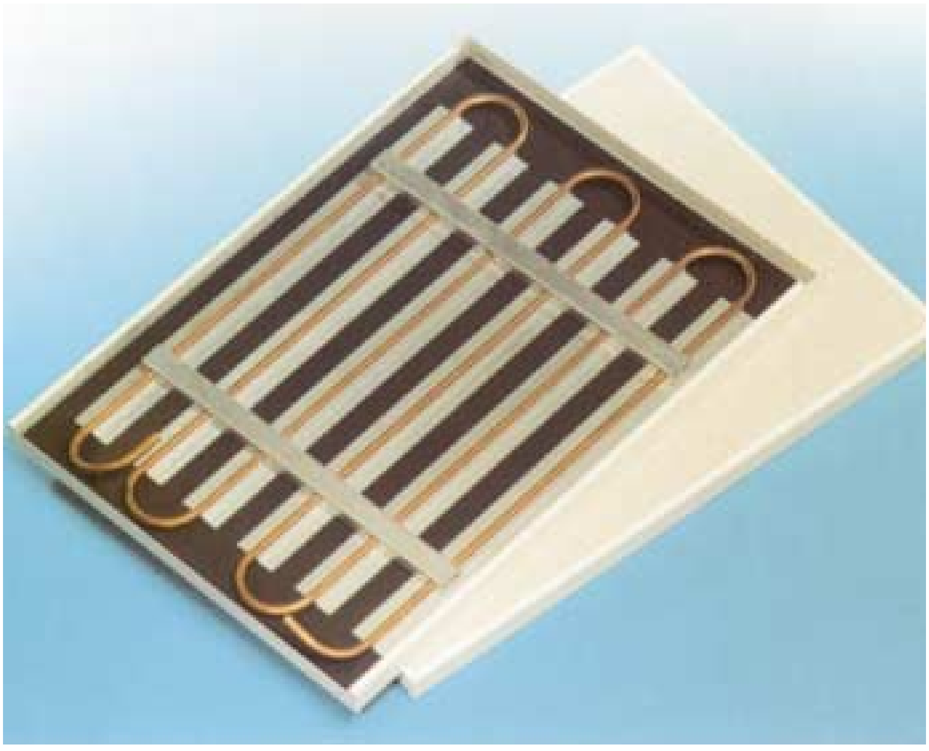
As unlike heaters in parapets heating ceilings have no effective protection against the cold air drop at cold facades, this cold air drop with the associated risk of draughts often poses the largest problem. To prevent a disruptive cold air drop glass with very low U-value must be used, depending on the height of the glazing, e.g. at $h = 1.5$ m $U \leq 1.8$ W/(m² · K).

In addition the heat requirement of the room must be so low that the requisite heating capacity of the ceiling (related to room area) amounts to a maximum of 35 - 50 W/m². With larger heating capacities higher air temperature stratifications occur on the one hand ($>$ 2 K/m at normal room height 2.5 - 3 m) and in addition the asymmetric radiation due to the warm ceiling exceeds the permissible limit value. At these low heating capacities, however, the heating needs at window ventilation in offices with a sufficient air exchange can hardly be assured ($n = 1 ... 2\ h^{-1}$).

Where rooms have a mechanical ventilation with a turbulent air distribution system, the air flow produced in this way reduces temperature stratification on the one hand and increases the convective heating capacity quota on the other, so that the indicated limit (35 - 50 W/m²) shifts significantly upwards.

Finally, the differences in layout and the application parameters for heating and cooling are tabulated.

14



15

Figure 14: Detail of SKS 5 convective cooling ceiling (visible installation)
Figure 15: KKS cooling ceiling in perforated metal tile with fleece

	Cooling	***Heating***
Major layout parameters	Max. possible cooling capacity (depending on make)	Comfort requirements
Spec. capacity		
$\dot{q}_{\text{active area}}$	***Radiant ceilings*** restricted by dew-point, typical 80 - 100 W/m²	***Radiant ceilings*** up to approximately 90 W/m² at low occupation density ($\vartheta_{flow} \approx$ 50°C)
	Convective ceilings max. about 150 W/m² at indoor air velocity $\leq$ 0.15 m/s	***Convective ceilings*** up to approximately 200 W/m² at low occupation density ($\vartheta_{flow} \approx$ 50°C)
$\dot{q}_{\text{room}}$	Depending on occupation density	Limited to 35 - 50 W/m² by comfort requirements (vert. temperature gradient and asymmetric radiation)
Capacity specifications	Very precise specifications possible (to DIN 4715)	Poses problems; influence of occupation density and temperature stratification
Comfort criteria		
Temperature stratification	Practically none	Depending on load, approx. 2 K/m at $\dot{q}_{\text{Room}}$ 40 - 50 W/m² (without ventilation)
Asymmetric radiation	Cool ceiling is felt as positive	Up to about $\dot{q}_{\text{Room}}$ 50 W/m² comfortable, above this the permissible asymmetry is exceeded
Indoor air velocities	$\leq$ 0.15 m/s (for capacities up to approx. 150 W/m²)	Cold air drop in the facade zone dependent on glazing height and U-value
Limitations		
$\dot{q}_{\text{active area}}$	150 W/m²	50 - 200 W/m² (depending on occupation density)
$\dot{q}_{\text{room}}$	Approx. 120 W/m²	35 - 50 W/m² (higher with mechanical ventilation)
U-value window	No influence	$\leq$ 1.3 W/m² K (3 m glazing height) $\leq$ 1.8 W/m² K (1.5 m glazing height)

Table 1:
Comparison of cooling and heating with thermally active ceilings

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[1] Glück, B.:
Grenzen der Deckenheizung - Optimale Heizflächengestaltung, HLH, Nr. 6, 1994

[2] Heisselberg, P.:
Stratified flow in rooms with a cold vertical wall ASHRAE Trans. 1994, V.100; PT.1.

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Technical Report 87/2002 e