International Energy Agency
Energy Conservation in Buildings and Community Systems

Literature review:
Side Effects of Low Exergy Emission Systems

March 2000

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This work has been performed under contract with Novem BV, the Netherlands Agency for Energy and the Environment, in the framework of the *Market Introduction of Low Temperature Heating Systems* – Programme, carried out on behalf of the Ministry of Economic Affairs and the Ministry of Housing, Spatial Planning and the Environment

The views and opinions of the authors do not necessarily state or reflect those of the Dutch government or Novem.

This report is a product of the Annex 37
working group and has not been submitted
for approval of the ECBCS Executive committee.
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1. Introduction

1.1. General

Over the past 25 years in many countries, natural gas has gained wide acceptance as an energy source for space heating. Today, most buildings with gas-fired central heating systems, are mostly designed for the temperature range of 90/70°C. In practice, these high temperatures are reached only occasionally, when heat demand is highest. Most of the time, especially where sophisticated control systems are used, heat emission systems operate at lower temperatures.

The use of Low Temperature Heating (LTH) systems presents a number of advantages energy-wise. More different heat sources are available for low temperature heating than for high temperature systems. Examples include waste heat from industrial plants and geothermal heat (with or without a heat pump). Also, in the case of LTH systems, heat losses during storage and distribution are lower than for traditional systems.

1.2. Heat emission systems

The present study confines itself to emission systems in buildings, such as radiators in traditional systems. Emitters in a LTH system require a larger surface area than those in a high-temperature system for the same heating capacity. Suitable options here are floor heating, wall heating and radiators with increased capacity. Air heaters and convectors are also well suited for LTH. Heat emission systems usually have a long service life. Heat generating systems typically last 15 to 20 years and pipework and radiators some 30 to 40 years. Suitable emission systems should be designed as a matter of urgency if LTH sources are to see a successful introduction.

1.3. Declining heat demand

A number of trends in the building construction industry call for heating systems to be rethought.
As more and more energy-saving features are added in new buildings, the required heating capacity continues to decrease. As a result, the peak demand during extreme cold is also lower, with the heat supply showing a lower amplitude. Heat within the building is better conserved, providing better damping. Thus, any heat added (by the sun, internal heat sources or heating system) is retained for a longer period of time. Especially the latter aspect means that we have more leeway as to the point in time where heat is added. The savings from a lower thermostat setting during nighttime or daytime diminish, as does the effect of thermal zones within the building. This trend calls for a constant supply of low-temperature heat rather than rapid heating during extreme cold. Current systems are designed especially with the latter aspect in mind. An LTH system is more suitable as regards the first aspect.

Most buildings inevitably have a number of colder surfaces, such as windows, and normal practice is to locate radiators in their vicinity. This becomes less necessary as thermally improved window glazing is used. An added advantage is that turbulent air currents are avoided.

1.4. Solar heating and control systems

Better insulation in combination with designs aimed at utilising passive solar energy poses the risk of overheating. Heat from incident solar radiation increasingly affects the interior climate as the amount of heat increases in proportion to the heat supplied by the heating system, especially in spring and autumn. Since solar radiation is characterised by wide fluctuations, it is essential that an effective thermal mass be provided within the envelope. Even then, when a sudden influx of solar radiation occurs, the emission system may continue to release heat even though the heat demand has gone. This causes the desired temperature to be exceeded. Emission systems such as floor and wall heating are usually applied in buildings that collect most solar radiation. This presents a number of advantages. The thermal mass in such designs is larger due to the presence of the heating system. The system is better able to respond to the influx of solar heat (assuming a suitable control system is used). The large surface area of the emission system ensures that local incident heat is better distributed over the occupied zone, e.g. in the case of North-South orientation. These advantages allow better utilisation of incident solar radiation, resulting in improved energy conservation.

Another important aspect is the self-regulating character of LTH systems. Since the temperature of the emission systems is only a few degrees higher than the indoor air temperature, the heat release decreases rapidly on a temperature increase. Conversely, heat release strongly increases on a temperature decrease.

1.5. Overheating

In summer conditions, the available thermal mass often is inadequate to prevent overheating. In that case, additional provisions are needed, such as ventilation (mechanical or natural), shading devices and/or cooling (passive or active). LTH systems, whether or not in combination with a suitable generator such as a heat pump, are particularly suited for providing a limited degree of cooling. Substantial cooling capacities can be achieved by including dew point control. Free cooling can be obtained by combining the system with a heat collector in the soil so that heat extracted from the soil during winter is returned in summer.

1.6. Heating-up allowance

Current methods of determining the required capacity of heating systems include an allowance for the extent to which heat is absorbed in the building fabric. This factor is increasingly important because of ever better insulation and lower ventilation losses. For well-insulated buildings, this factor ranges from 30 to 40%. It can be lower for LTH systems since here the wall or floor is heated directly and the proportion of radiant heat is higher. It can be reduced still further given that the heating pattern is more uniform; this does not apply to convectors and air heating.

1.7. Air quality

Air exchange between the indoor and outdoor environments is reduced by sealing and more accurate control of ventilation systems. This may result in degradation of the indoor air quality. Especially the air temperature has a major effect on how 'fresh' the air is perceived to be. At low temperatures the air is perceived to be better and irritation of the mucous membranes etc. is less likely to occur. An LTH system gives a higher proportion of radiant heat and so offers the same level of thermal comfort at a lower air temperature (this does not apply to convectors and air heating). An added advantage is that the relative humidity is higher at the same moisture content. In this way, dry air, a common complaint of public buildings, is prevented in winter. Floor and wall heating systems also have a beneficial effect on mite populations.

1.8. Systems considered

This study distinguishes between five heat emission systems:
– floor heating;
– wall heating;
– enlarged radiators;
– enlarged convectors;
– indirectly fired air heating.

These systems have been selected inasmuch as they are specially designed, or can readily be adapted, for low temperature heat sources. An LT heat source is defined here as one where water is used as medium at a temperature not exceeding 55°C.

For the purposes of a comparative performance evaluation of LTH systems we have opted for a reference system consisting of radiators and designed for 90/70°C, as widely used in dwellings.
Such comparison is unsuitable for air heating and convectors, since these have distinctly different properties and are intended for different applications. For proper assessment of the merits of LTH with these systems we have used as reference a similar system with a high-temperature heat source.

1.9. Literature search

In the light of the aforementioned trends, the time seems ripe for large-scale introduction of LTH systems. In order for such introduction to be successful, a better understanding is needed of the following aspects:
– thermal comfort;
– air quality;
– energy performance.

The following aspects need to be considered also:
– safety;
– cost;
– space required;

- acoustic comfort;
- maintenance, reliability, cleaning, etc.

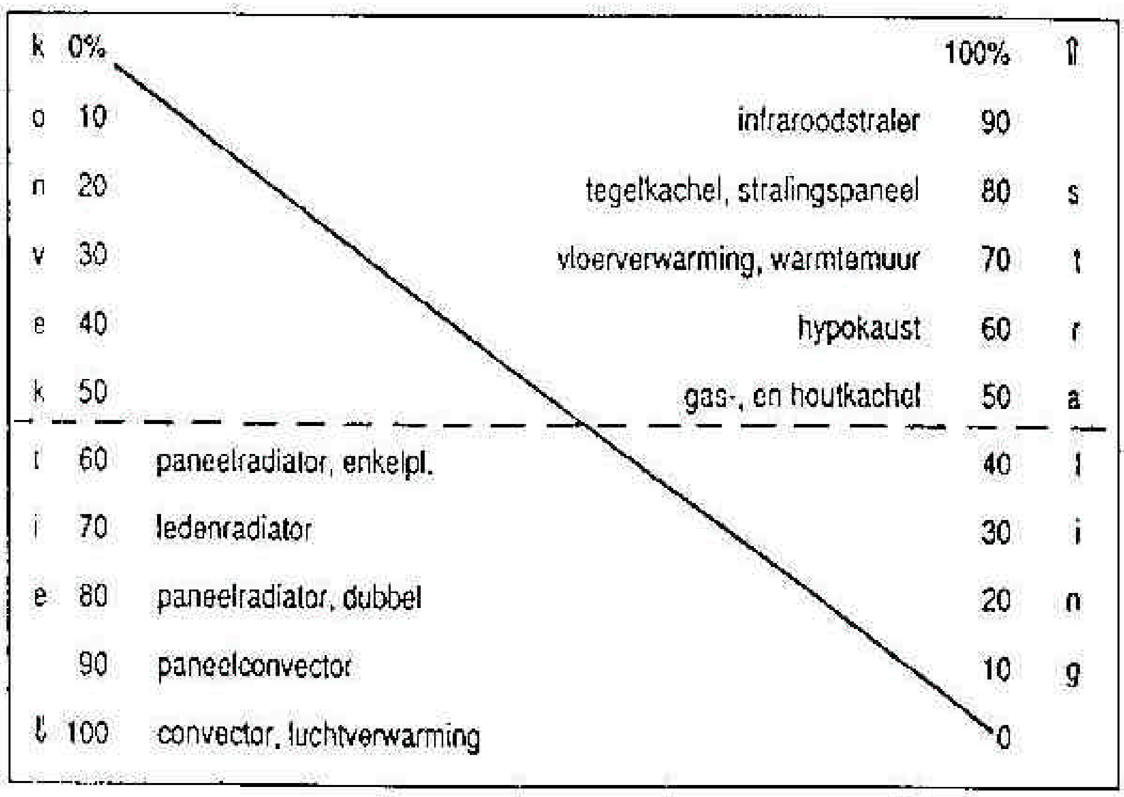
In the framework of IEA Annex 37 a literature search in the area of LTH systems is carried out. In this study the characteristics of LTH emission systems are compared with those of a traditional system based on radiators or air heating with water at 90/70°C. This comparison is used for assessing the merits of a low temperature heat source, with particular reference to the first three aspects listed above. Important properties are listed in Table 1.

The following sections state the literature that has been found on each aspect. Each section begins with a proposition, followed by supporting information found in literature.

Table 1: Different distinguishing marks of Low Temperature heating emission systems in relation to High Temperature systems

Quality aspect	**LTH item**	**Lower temperature transport medium**	**Lower temperature emission system**	**Larger surface emission system**	**Larger volume transport medium**	**Larger heat capacity**	**Larger part radiation transfer**	**Integration in building system**	**Applicability for cooling**	**Total system**
Thermal comfort	Air temperature	---------------	---------------	---------------	---------------	---------------	x			
	Vert. temperature gradient	---------------	---------------	x						
	Temperature asymmetry	---------------	x	x						
	Surface temperature floor	---------------	---------------	---------------	---------------	---------------	---------------	x		
	Temperature fluctuation	---------------	x	---------------	---------------	x				
	Heating up velocity	---------------	x	x	---------------	x	---------------	x		
	Temperature exceeding	---------------	---------------	---------------	---------------	---------------	---------------	---------------	x	
	Air velocity	---------------	x	x						
	Relative humidity	---------------	---------------	---------------	---------------	---------------	x	x		
	Occupants acceptation	---------------	x	x	---------------	---------------	x	---------------	x	x
Indoor air Quality	Airborne particles	---------------	x				x			
	Mites	---------------	---------------	x	---------------	---------------	---------------	x		
	Enthalpy	---------------	---------------	---------------	---------------	---------------	x			
	Odour nuisance	x	x	---------------	---------------	---------------	---------------	x		
Energy	Transmission losses	---------------	---------------	x	---------------	---------------	x	x		
	Ventilation losses	---------------	---------------	---------------	---------------	---------------	x			
	Distribution and control losses	x	x	---------------	---------------	x				
	Transport energy	---------------	---------------	x	x					
	Solar and internal heat gains	---------------	x	x	---------------	x	---------------	---------------	x	
	Metered energy use	---------------	---------------	---------------	---------------	---------------	---------------	---------------	---------------	x
Other aspects	Safety	x	x	---------------	---------------	---------------	---------------	x		
	Construction bound moisture	---------------	---------------	x	---------------	---------------	---------------	x		
	Building regulations	---------------	---------------	---------------	---------------	---------------	---------------	x	---------------	x
	Costs	---------------	---------------	x	x	---------------	---------------	x		

Figure 1: Global distinction between heating emission systems as a part of convection and radiation



2. Thermal Comfort

2.1. Air temperature

Proposition:

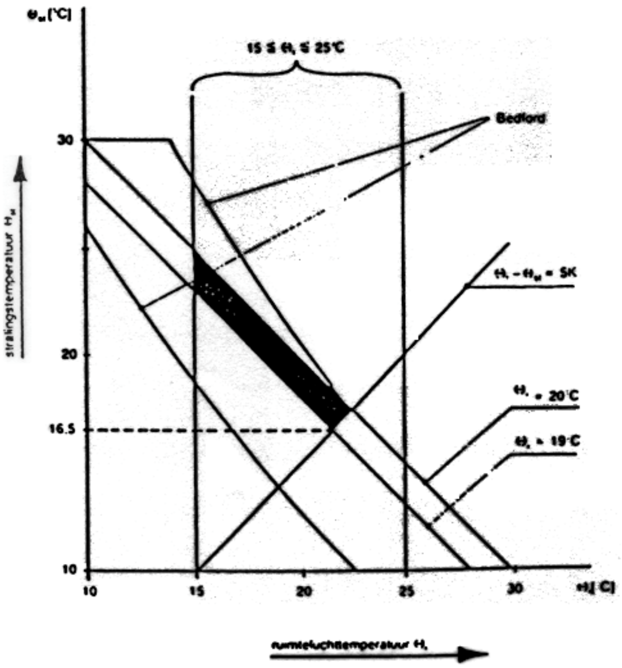
Both radiant temperature and air temperature influences thermal comfort of an individual. A lower air temperature may compensate for a higher radiant temperature. Consequently, LTH systems produce more radiant heat than traditional systems, so allowing a lower air temperature. Users perceive this as a benefit.

Supporting information:
Comparison of heating systems indicates that wall and floor heating systems produce relatively large amounts of radiant heat, i.e. approximately 70% (Figure 1, source: lit [1]). Convectors and air heating emit 90% of heat through convection. Some 20 to 40% of the heat emitted by radiators is radiant.
The values given in the figure are well in agreement with measured values cited in literature. Zollner (lit [2]) found that 60 to 75% the heat from floor heating is radiant. For heated walls this is 50 to 70% (lit [3]). The latter study reports that the radiant proportion decreases with increasing temperature of the heating element (or the temperature of the heated wall). This indicates that high-temperature radiators emit a smaller proportion of radiant heat. In this respect, low-temperature (LT) radiators have an advantage over high-temperature (HT) radiators. Apparently, convective transfer decreases more strongly on a decrease in temperature than does radiant transfer.

Various sources, such as lit [4], report that radiant heat is more comfortable than convective heat. This is because a high proportion of radiant heat (i.e. a relatively low air temperature and a relatively high ambient temperature) often occurs outdoors, where it is experienced as highly comfortable.

Heating systems whereby a large proportion of heat is transferred through radiation approach this situation most closely. Unfortunately, there is only little literature to support this. It would be useful to conduct laboratory tests enabling a comparison of the effects of radiant heat and convective heat on comfort. Such tests should take place in a neutral thermal environment; this can be accomplished by keeping the operative temperature (the mean of the air temperature and the mean radiant temperature) constant at, say, 22°C, at air velocities lower than 0.2 m/s. In these tests, the experimental subjects are exposed during a number of sessions to different combinations of air temperature and radiant temperature, for instance first an air temperature of 20°C and a mean radiant temperature of 24°C and next an air temperature of 24°C and a mean radiant temperature of 20°C. In each session the subjects should rate not only thermal comfort but also the *quality* of the interior climate.

Figure 2: Comfort criteria for air and radiant temperature



Θst [°C]
15 ≤ Θl ≤ 25°C
Bedford
30
20
16.5
10
stralingstemperatuur Θst
Θl − Θst = 5K
Θl = 20°C
Θl = 19°C
10
15
20
25
30
Θl [°C]
ruimteluchttemperatuur Θl

According to Fanger & Olesen (lit [8]), such tests have been conducted but the results have never been published. In any case, minor variations of the operative temperature made no difference in appreciation. Air velocities do play a role here. High air velocities may cause a draught at lower air temperatures. Typical air velocities are decreasing as a result of current building practice, with improved sealing, low-loss glazing, improved ventilation grilles and the effects of heat emitting systems themselves (see 2.9).

Lit [9] indicates that, in normal conditions, thermal comfort is largely determined by the air temperature and radiant temperature. It refers to an area in which the temperature resulting from a number of combinations offers equivalent comfort (Figure 2). This resultant temperature is defined as follows.

$\Theta_i = (\Theta_1 + \Theta_{st})2$,

where

Θ_i = resultant temperature
Θ_1 = air temperature
Θ_{st} = radiant temperature

Lit [9] cites the following criteria:
– $19°C \leq \Theta_i \leq 20°C$;
– $\Theta_1 - \Theta_{st} \leq 5°C$;
– $15°C \leq \Theta_1 \leq 20°C$.

From these criteria follows a maximum radiant temperature of approximately 25°C. Field tests indicate that systems producing a high proportion of radiant heat are well appreciated by the occupants. Although it is not possible here to determine in how far this is due to a lower air temperature, it is unlikely to detract from the high degree of satisfaction with wall and floor heating systems (refer to 2.11).

Systems emitting a high proportion of radiant heat are felt to be more comfortable for a number of reasons, four of which are cited here.
– Radiant heat results in a more uniform temperature distribution and lower air velocities. It is especially the lower velocities that have a beneficial effect (2.8). This is the case with large heating areas in particular. With small radiating elements, radiation intensity decreases with the distance, which is why a convective system may produce a better temperature distribution;
– At a lower air temperature, the relative humidity is higher and the rate of evaporation is lower (2.9);
– Radiant heat (infrared radiation) widens the blood vessels and improves blood circulation at the skin. Persons with low metabolism, such as the elderly and infants, are sensitive in this respect (lit [5]);

Radiant heat results in the surface temperatures of the walls approaching that of the human body, i.e. the temperature of clothing and bare skin. As a result, the amount of heat emitted to the environment through radiation is only low. Indeed, heat may even be *supplied* through radiation.

The latter assumption is an interesting one and may call for further explanation (lit [4]). Each and any body (above absolute zero) emits heat. The warmer the body, the more heat it emits. The amount of heat emitted is also dependent on the temperatures of the surfaces surrounding the body and on the emission coefficients of the surfaces of the body and of the surfaces surrounding the body. (For that matter, the emission coefficient is practically the same for most materials, i.e. about 0.90 to 0.95 (lit [10]).

Consider by way of example a person in a room with a relatively cold window. The person will feel it is exposed to cold radiation, as the body emits more heat to the window than the window emits to the body. So we have a net loss of radiant heat. Lit [11] reports that the mean surface temperature of the human body, i.e. that of clothing and bare skin), in winter conditions is about 25 to 26°C. Thus, to prevent the body from emitting heat to the environment, the mean temperature of walls, floors, ceilings, etc. should be the same. This is the case in buildings having wall and floor heating. Only seldom will it be higher than 20-21°C in buildings with air heating or radiators.

At essentially neutral ambient temperature, heat is mainly emitted by convection, evaporation and human breathing. The human body is well able to control the body temperature through evaporation and hence readily responds to physical thermal demand. It is better able to accommodate fluctuations by convection than by radiation, inasmuch as an insulating layer forms in the boundary layer around the skin. That is why temperatures of 80 to 100°C can be endured in for instance a sauna. This protective system is much less flexible for heat transfer through radiation. For this reason, it is best for heat transfer through radiation to be as low as possible. In that case, the temperature of the human body is primarily controlled by convection, evaporation and the respiratory process. The human body is well equipped for this purpose.

Conclusion:

Heat emission systems in a LTH system transfer more heat through radiation than via the air. This normally makes for a high level of comfort. Wall and floor heating produce more radiant heat (50-75%) than radiators (20-40%). Given the mean surface temperature of the human body, this means that in the former case radiant heat losses to the environment need not be made up for by a high air temperature. Project evaluations indicate that thermal comfort provided by LTH systems is equal to or even better than that of other systems. Small-scale tests have shown that thermal comfort is not affected by minor variations in the air and radiant temperatures. Yet, the impression persists that body temperature is controlled more easily by convection and evaporation than by radiation. Thus, a 'radiation-neutral' environment is to be preferred.

Rating of emission systems

(Note. This is a comparison of HT and LT heat sources, not of for example air heating and radiator heating).

proportion of radiant heat	**rating**	**notes**
floor heating	+++	high proportion of radiant heat and large radiating area
wall heating	++	less than floor heating
enlarged radiators	+	less than wall heating
LT convectors	0	neutral relative to HT systems
LT air heating	0	neutral relative to HT systems (the negative effect of air heating in comparison with radiators decreases as the insulation level increases)

Figure 3: Vertical temperature gradients for different heating systems

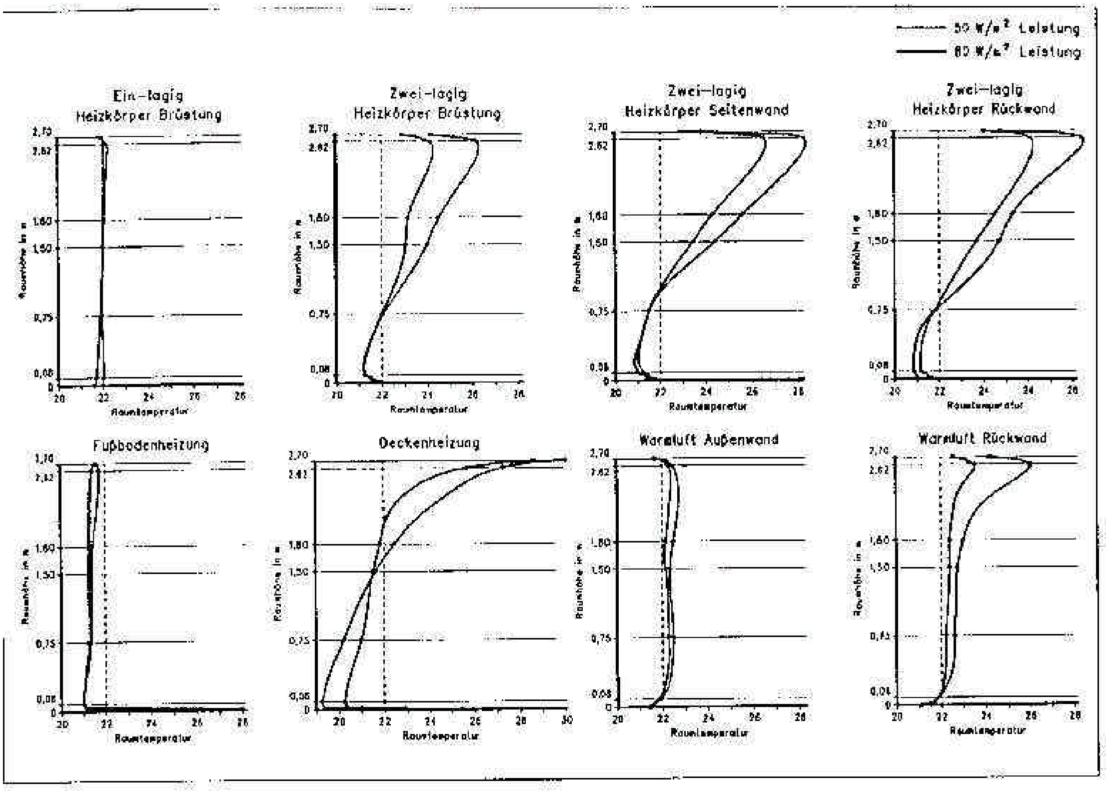


Table 2: Measurement results thermal comfort situation in practice (Ecolonia project the Netherlands)

Heating system	Temperature difference between 0,1 m and 2,2 m
Radiators	2,4 K
Floor heating	< 0,8 K
Wall heating	2,1 K
Air heating	1,6 to 2,5 K

2.2. Vertical temperature gradient

Proposition:

Heat is released more uniformly by floor heating systems than by radiators, leading to less air circulation. This results in a smaller vertical temperature gradient. Thus, dissatisfaction because of a large temperature difference between the head height and the ankle height is less likely with floor heating than with radiators.

Supporting information:
In most rooms, the air temperature is lowest at the floor and highest at the ceiling. Too large a gradient here will cause the occupants to experience thermal discomfort: they may feel the head is too warm or the feet are too cold, even though the body as a whole is thermally neutral. Limit values for the vertical temperature gradient are specified in various standards. NEN-ISO 7730 (lit [12]) requires that the temperature difference between 1.1 m and 0.1 m (the head height and ankle height) above the floor shall not exceed 3°C for light, mainly sedentary activity. (Normal practice is to stick to a gradient of 3°C per metre).
In some cases (lit [13]), the vertical temperature gradient must not exceed 2°C. Obviously, in general the aim should be to achieve the smallest possible gradient.

The vertical temperature gradients created by different heating systems have been measured on many occasions. See Figure 3, (lit [14]), Figure 4 (lit [15]) and Figure 5 (lit [16]).

Note that the curve at the far right in Figure 3 relates to a heat demand of 80 W/m^2 and the one at the far left to 50 W/m^2. The second curve from top left (Zwei-lagig Heizkörper) best matches the reference system utilising radiators.
The bottommost bars in Figure 5 represent the floor temperature, not the air temperature just above the floor.
Such measurements have also been conducted in the Netherlands, in dwellings having different heating systems. In a number of homes in the “Ecolonia” demonstration project, thermal comfort was measured in winter for about ten days, with the outside temperature ranging from 4 to 8°C. The results (De Vries) are shown in Table 2 (lit [17]).

Figure 4: Vertical temperature profiles in middle of the room for different heating systems

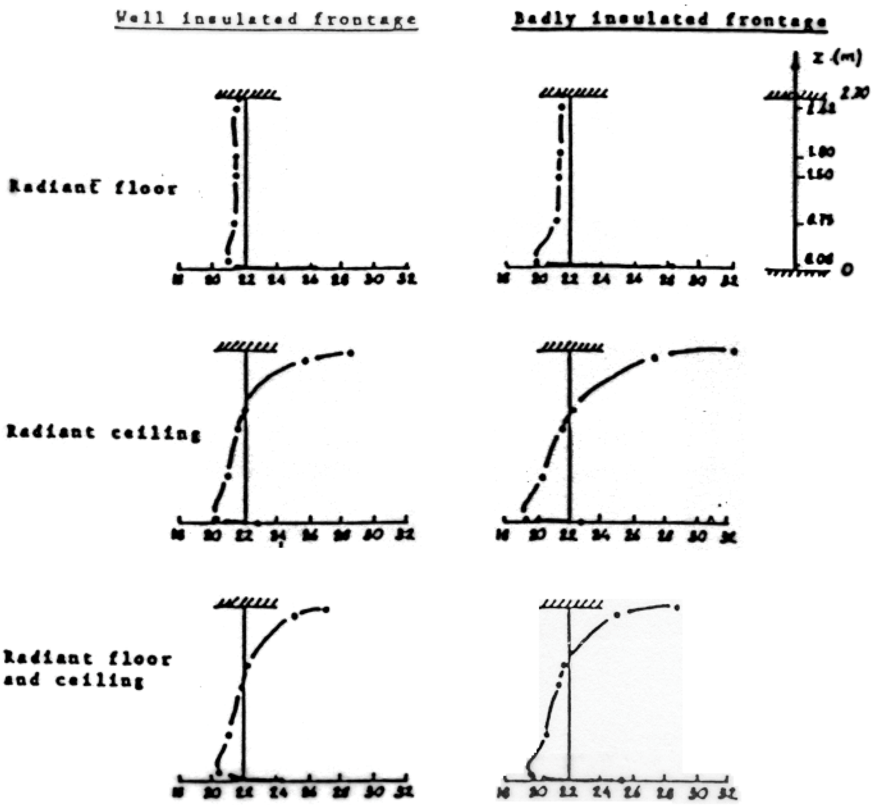
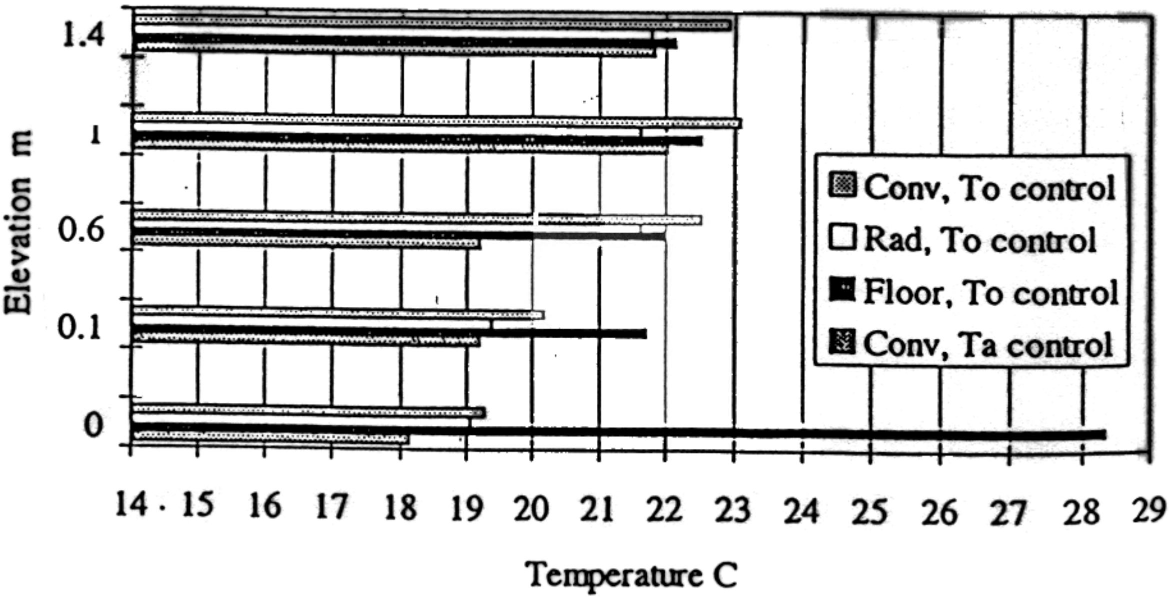


Figure 5: Vertical temperature distribution in middle of the room for different heating systems and controls



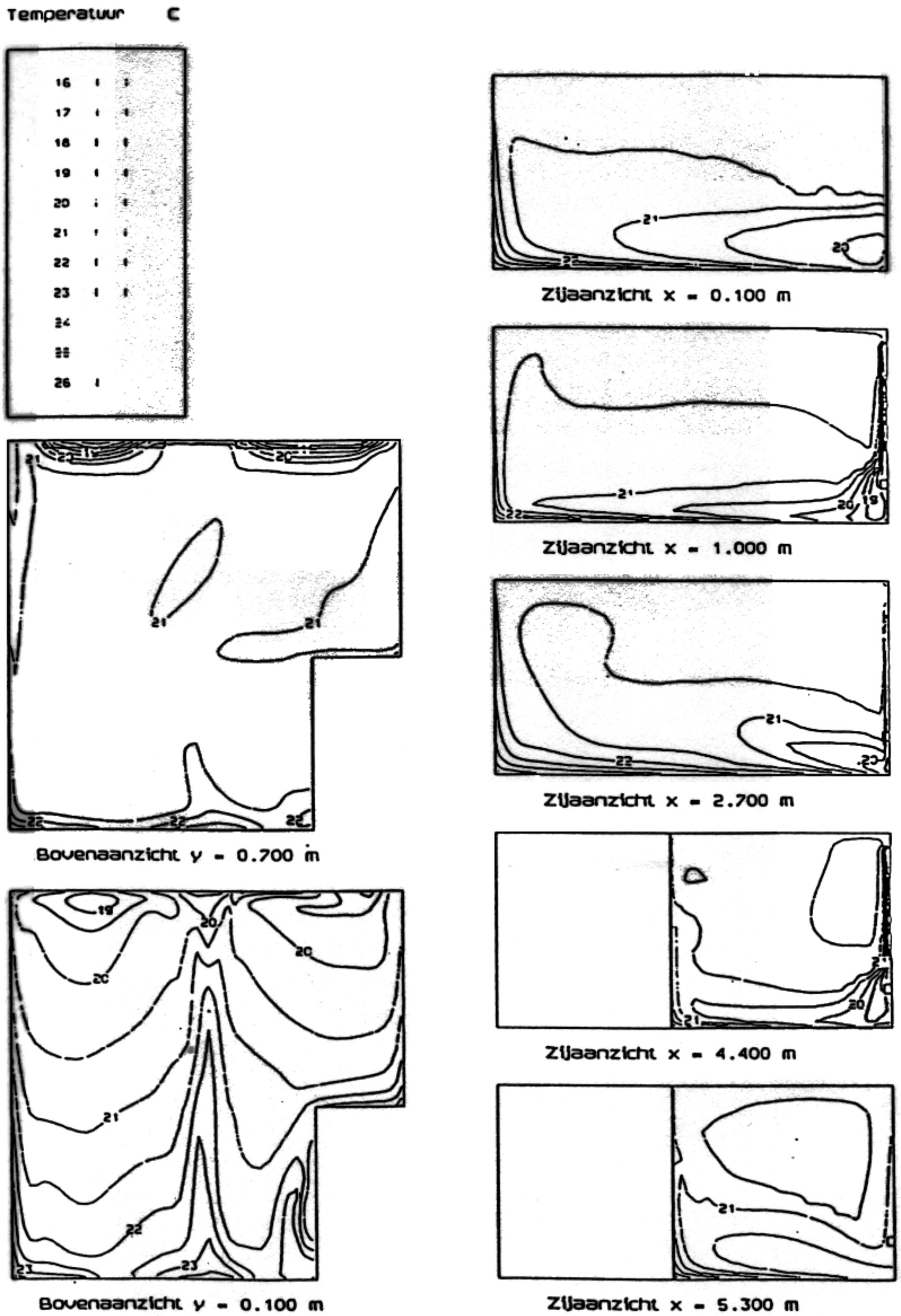
The researchers concluded that climatic conditions in homes with floor heating are most favorable in that the vertical temperature gradient is very small here. The air flow patterns for wall heating and radiators proved to be quite similar (lit [18]).

Van Dijk et al. (lit [19]) recently computed the vertical temperature gradient for different heating systems using a CFD simulation program. Simulations were run for the living room in a reference dwelling at an outdoor temperature of 5°C. This dwelling, a terraced house (selected from (lit [20]), has a building envelope with following properties: R_c value = 3.0 m^2 K/W and $U_{windows}$ of 2.4 W/m²K. Note that the glazing is only a little better than standard double-glazing ($U_{windows}$ = 2.8 $W/m^2.K$). Current building practice most countries is to install better glazing ($U_{windows}$ = 1.8 to 1.2 $W/m^2.K$).

Van Dijk, too, found that floor heating gives the best vertical temperature gradient. On no occasion was it significantly greater than 1°C. The high floor temperature affects only a small (boundary) air layer immediately above the floor surface. The air temperature decreases as the distance from the floor increases. A temperature increase was observed just beneath the ceiling. The area affected by the temperature drop along the windows is limited to a narrow band below the windows. With HT radiator heating, the vertical temperature gradient was about 3°C. With LT radiator heating, the gradient was about one degree narrower. With wall heating, the air temperature difference between the ceiling and the wall was comparable to that encountered with HT radiator heating, i.e. about 3°C. With wall heating the largest gradient occurs at the centre of the room whilst with radiator heating it occurs at the floor and the ceiling. The authors suspect therefore that HT radiator heating is more likely to lead to dissatisfaction. The computational results are shown in Figure 6 (lit [19]).

Summarising, the conclusion is that with floor heating the vertical temperature gradient will not normally exceed 0.5 to 1°C across the height of the room . It is even somewhat smaller between 1.1 m and 0.1 m. The figures indicate that thermal comfort with wall heating and LT radiator heating is somewhat better than with HT radiator heating and somewhat less than with floor heating.

Figure 6: Calculated temperature distribution for floor heating (CFD modeling)



A premise with HT heating has all along been that the high amount of radiant heat emitted by radiators compensates for any cold radiation from windows. That is why radiators are preferably located in the vicinity of windows. Now that building elements are produced with increasingly better levels of insulation, this premise has lost much of its truth. With improved insulation, heating systems producing a smaller vertical temperature gradient are more appropriate. Since warm air tends to rise, the heat should preferably be introduced into the room at the lowest possible temperature over as large an area as possible.

Conclusion:

Various research programs have shown that LT systems produce a narrower vertical temperature gradient than do traditional radiator systems. A gradient is hardly discernible with floor heating. If properly designed, wall heating and air heating systems, too, produce very small gradients. Current radiator systems produce a gradient that is barely good enough, if at all, for thermal comfort. Better glazing reduces the need to compensate for cold surfaces, which makes a small temperature gradient all the more important. With all systems tested, the gradient decreases with lower heat emission rates (because of better insulation or heating-curve control.

Ratings of emission systems reviewed

Vertical temperature gradient	**rating**	**notes**
floor heating	+++	Uniform, low temperature and large area
wall heating	++	If located against exterior wall
enlarged radiators	++	Due to lower temperature
LT convectors	++	Due to lower temperature
LT air heating	++	If air is supplied at exterior wall

2.3. Temperature asymmetry near windows

Proposition:

Wall and floor heating systems are more likely to cause local thermal discomfort due to radiant temperature asymmetry of e.g. cold windows. This is normally overcome by adding a HT radiator at windows. It can be prevented for LT systems by using well insulated building elements and higher peripheral temperatures.

Figure 7: Percentage dissatisfied as function of radiant asymmetry by cold vertical plane

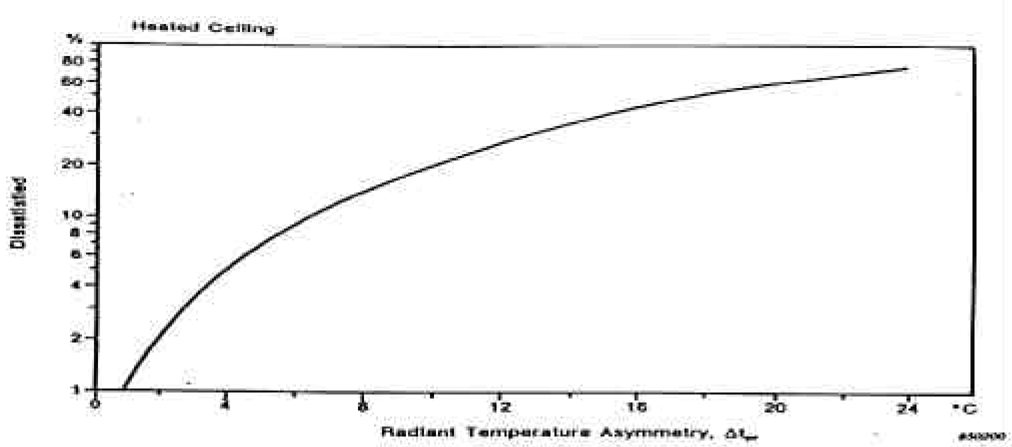


Fig. 5. Percentage of dissatisfied as a function of the radiant temperature asymmetry ? t_{pr} from a heated ceiling

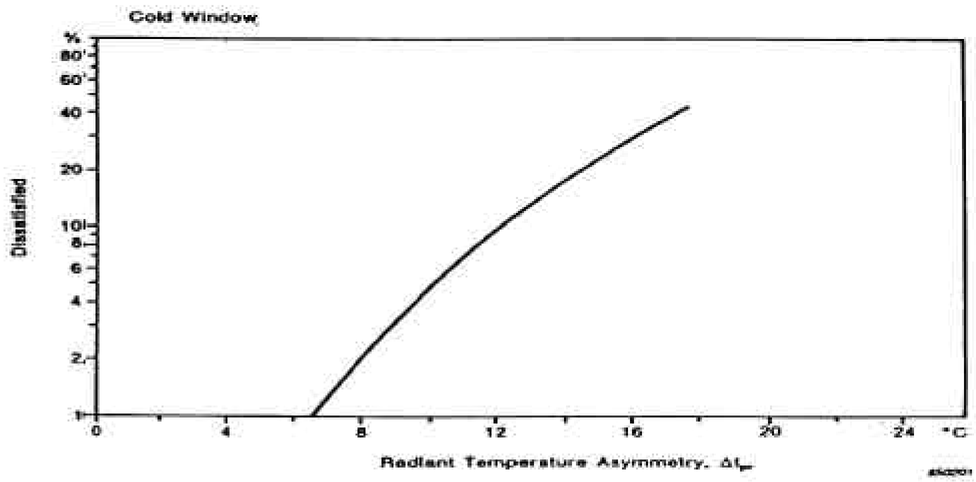


Fig .6. Percentage dissatisfied as a functio of the radiant temperature assymetry ? t_{pr} from a cold window/wall

Supporting information:
The main cause of radiant temperature asymmetry in homes and offices are cold windows. Radiant temperature asymmetry is defined as the difference between the radiant temperature perceived from one side of an infinite, flat plane relative to the other side of that plane. For example: The radiant temperature asymmetry in a room with at one end a glazed facade infinitely wide and high is equal to the difference between the surface temperature of the facade and that of the opposite wall.

Research (Figure 7, lit [21]) has revealed that the horizontal radiation asymmetry brought about by a cold vertical plane, such as a window, results in a Predicted Percentage Dissatisfied (PPD) of 5% if the radiant temperature asymmetry is 10°C. No thermal discomfort is experienced where the radiant temperature asymmetry is not more than 6°C.

This subject is addressed by a number of standards and building regulations. NEN ISO o 7730, for instance, requires that radiant temperature asymmetry of maximum 10°C for cold vertical surfaces such as windows. This means that the surface temperature of a window must be at least 10°C at a mean wall temperature of 20°C.

The horizontal radiant temperature asymmetry for windows and with radiator-based heating is comparable with that encountered with wall and floor heating. Olesen (lit [22]) has investigated radiant temperature asymmetries for different heating systems in a controlled environment, which represented a well insulated dwelling with standard double-glazing. Measurements were conducted at outdoor temperatures of –5°C and +4°C. The results are shown in Table 3 (lit [22]).

'Floor non-uniform' refers to a floor heating system in which the tubing is laid more densely in a 0,6 m band at the window for higher heat supply. The radiant temperature asymmetries were measured in both the vertical and horizontal planes at one metre from the exterior wall and at a vertical distance of 0,6 m from the floor.

Table 3: Radiant temperature asymmetry for different heating systems

TABLE 3. Radiant Temperature Asymmetry described by the Plane Radiant Temperature Difference in Relation to a Vertical (VER, Back-Front) and a Horizontal (HOR, Up-Down) Plane 0.6 m from the Floor and 1.0 m from the Frontage (Postion 27 on Fig. 2)

		HEATING METHODS																	
Outside temp.	Infil-tration rate	RADIATOR 1.1 frontage		CONVECTOR 1.2		RADIATOR 1.3 backwall		CEILING 2.1		FLOOR 3.1 uniform		FLOOR 3.2 non uniform		WARM AIR 4.1 backwall		WARM AIR 4.2 frontage		SKIRTING BOARD 5.1	
°C	h^{-1}	VER K	HOR K	VER K	HOR K	VER K	HOR K	VER K	HOR K	VER K	HOR K	VER K	HOR K	VER K	HOR K	VER K	HOR K	VER K	HOR K
-5	0	-0.1	-1.8	0.5	-1.0	3.2	-0.2	3.3	1.2	3.2	-2.8	1.8	-2.8	3.1	0.6	1.8	-0.3	2.0	-0.7
	0.4	-1.4	-2.2	-0.2	-1.3	3.4	-0.1	3.5	1.7	3.2	-4.0	2.1	-4.2	3.3	1.0	1.8	-0.3	1.9	-1.3
	0.8	-2.2	-2.0	-0.7	-1.4	3.5	0.0	3.5	2.2	3.4	-4.6	2.3	-5.0	3.5	1.5	1.7	-0.3	0.6	-1.7
+4	0.4	-0.8	-1.4	-0.2	-0.9	3.6	-0.2	3.5	1.0	2.4	-2.4	0.9	-2.6	2.3	0.5	0.6	-0.3	1.0	-0.9

The table indicates that none of the heating systems result in a horizontal radiant temperature asymmetry greater than 10°C. It is noteworthy, however, that for both floor heating systems the asymmetry (or cold radiation due to a cold window) is on the high side, albeit well within the 10°C limit , i.e. from +2.5 to +5°C. (With radiators, this is about –1 to –2°C).
The results are somewhat better if $U_{windows}$ <2,0 W/m^{2}K.

These results are in agreement with those of Erhorn & Szerman (lit [23]), who investigated, with the aid of a 'thermal mannequin' , the effects of different heating systems and of the locations of the heating elements on the heat flux density at various parts of the body.

Differences in heat flux density are known to cause thermal discomfort much in the same way as radiant temperature asymmetry if the bi-directional radiation difference exceeds 23 W/m^2 (lit [24]).
The results of the investigation are shown in Figure 8 (lit [23]) for a level of activity of 70 W/m^2 (or a metabolic rate of 91.2 Met), corresponding to light or sedentary activity. Insulation provided by clothing was 1.0 clo (winter clothes). The chest height was 90 cm and the height of the window was 1.5 m. In each test the dummy was facing the window. R in the figure means the right-hand side of the body (thus, heat is radiated here to the right), l stands for left-hand side, F for front, B for back and H for head, i.e. upward radiation. The outdoor temperature was –10°C. The U value of the exterior wall was varied during the tests.
Figure 8 indicates that radiant heat distribution is most uniform with a radiator beneath the window. At a mean U value of the exterior wall of 1.6 W/m^2.K, the difference in heat flux density never exceeds 5 W/m^2, whilst with floor heating this difference is almost 10 W/m^2 (difference between head and front). In no instance does the measured heat flux density exceed the thermal comfort limit of 23 W/m^2, not even at the higher U values.
The writers of the article conclude that radiator heating beneath the window provides the highest level of comfort where cooling of different parts of the body due to radiation is the main criterion (lit [23]).
However, if the exterior wall is thoroughly insulated, the differences are so small that the type of heating system and its location relative to the window do not really matter.

As mentioned earlier, less than 5% of people are dissatisfied when the radiant temperature asymmetry from cold windows is max. 10°C (lit [21]).
For glazing with a U value of 1.5 W/m^2.K and an outdoor temperature of –10°C, the interior glazing temperature is 14°C (lit [10]). In worst-case conditions (standing or being seated at a large window) the mean radiation temperature in the direction of the glazing is 14°C. Assuming a mean temperature of 20°C for the floor, walls and ceiling, the radiant temperature asymmetry is –6°C. This means that, if low emitting or triple glazing and wall heating are used, thermal comfort is satisfactory even at an exterior temperature of –10°C.

Conclusion:

Radiant temperature asymmetry from cold windows may lead to discomfort if it is not compensated for by radiators. The effects are mitigated by double-glazing and are tolerable at outdoor temperatures down to about –3°C. If low emitting or triple glazing is used, the asymmetry has no discernible effect at outdoor temperatures down to –10°C even if wall heating is used. Unnecessary, some compensation for LT systems is possible by applying warmer boundary zone for floor heating or warm facades for wall heating.

Ratings of emission systems reviewed

Radiant temperature asymmetry	**Rating**	**Notes**
floor heating	0	Assuming insulation to current building regulations, worse than radiators
wall heating	0	Ditto, but better than floor heating
enlarged radiators	0	Sale as wall heating
LT convectors	0	Neutral in comparison with HT systems
LT air heating	0	Neutral in comparison with HT systems

Figure 8: Direction depending heat flux for different heating systems

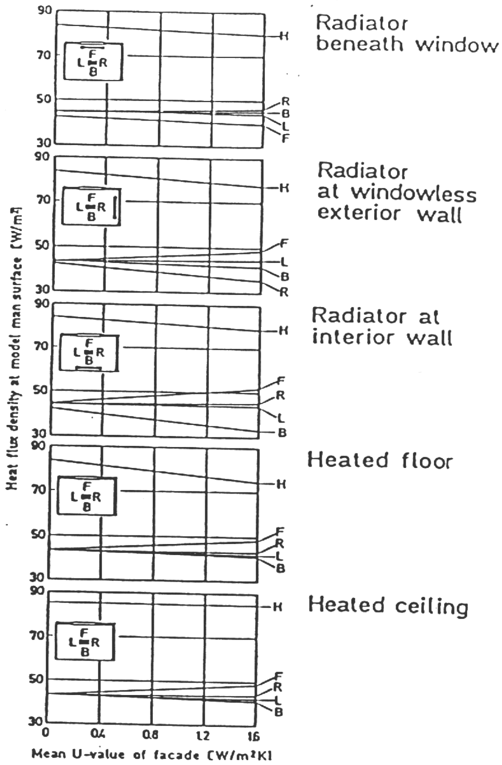
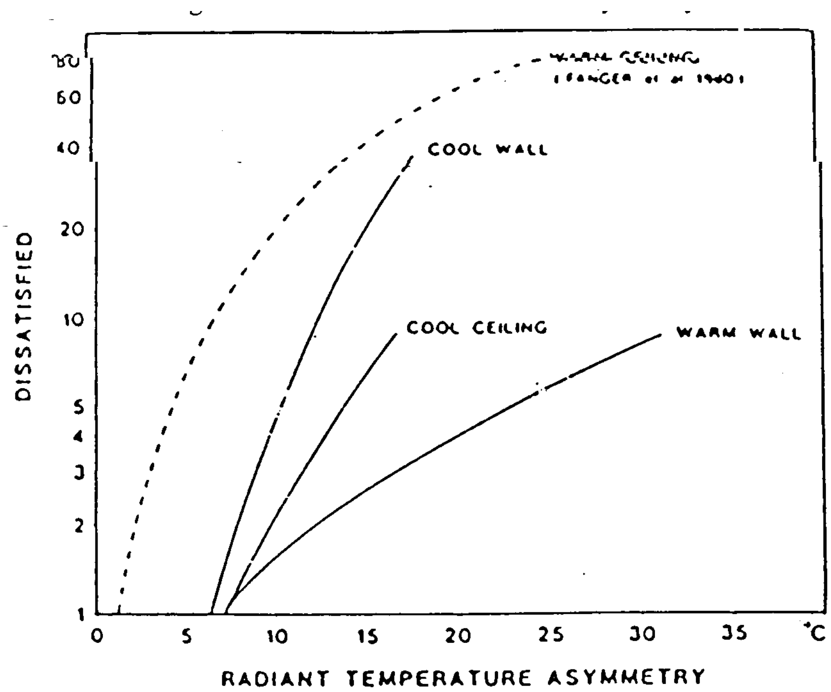


Figure 9: Percentage dissatisfied as function of radiant asymmetry for different loads



Radiant temperature asymmetry for other planes

> Wall and floor heating systems are more likely to cause local thermal discomfort due to radiant temperature asymmetry or too large surface temperature difference between opposite surfaces such as floors and ceilings. The effects are only limited and can be prevented by moderate heating of large surface areas.

Supporting information:
Standards for interior climates, e.g. NEN ISO 7730, specify requirements only for the radiant temperature asymmetry resulting from either a cold vertical surface or a warm horizontal surface located over the occupants (ceiling heating).
The requirements are:

- For vertical surfaces (windows): max. 10°C;
- For warm, overhead horizontal surfaces: max. 5°C.

Thus, the requirement for vertical surfaces is more stringent than for horizontal planes. This is because people are more sensitive to radiant temperature asymmetry brought about by warm or cold surfaces located above or below them than for those brought about by vertical warm or cold surfaces.

<u>Radiant temperature asymmetry brought about by warm walls and floors</u>
The standards do not specify any requirements for warm, vertical surfaces (heated walls), cold or cooled ceilings and warm horizontal surfaces (heated floors) beneath the feet.
Tests have shown that in the converse situations, i.e. a warm vertical surface instead of a cold vertical surface, etc., the occupants are less likely to be dissatisfied (lit [25]; lit [26]. See also Figure 9 in (lit [25]).

This means that the standards for wall heating and floor heating may be more lenient than those relating to glazing and heated ceilings. Table 4 shows the limit values for PPD max. 5% (Fanger, lit [26].

Limit values for the radiant temperature asymmetry from floor heating were nowhere to be found in the literature. For the time being, it is assumed that the same limits apply as those relating to a cooled ceiling, i.e. 14°C. Lit [27] cites figures based on 10% PPD. The corresponding maximal radiation asymmetry for warm walls is 34°C and for cooled ceilings 18°C.

Table 1: Limited radiant temperature asymmetry at a PPD = 5%

Warm ceiling	**Cold plane (window)**	**Cold ceiling**	**Warm wall**
< 5 °C	< 10 °C	< 14 °C	< 23 °C

The temperature of heated walls should preferably not exceed 35°C; assuming the temperature of the opposite wall is 20°C, radiant temperature asymmetry will never be more than 15°C (<23°C). Heated floors should not be warmer than 29°C, in which case the horizontal radiant temperature asymmetry will only seldom exceed 9°C (<14°C).

The heating effect of a HT radiator diminishes quadratically with distance. The thermal effect of radiant heat, on the other hand, increases by the third power. Radiation intensity increases with increasing temperature. The large heat-emitting surfaces with floor and wall heating have a beneficial effect. Such effect is smaller for enlarged radiators. Convective heat, including that from air heating and convectors, also heats up the building fabric along which the air flows. Here, the difference between HT and LT is only relevant to convectors, since , with air heating, the air supply temperature is always limited in the interest of comfort. Air heating systems give better performance than HT radiators in long rooms with cold walls.

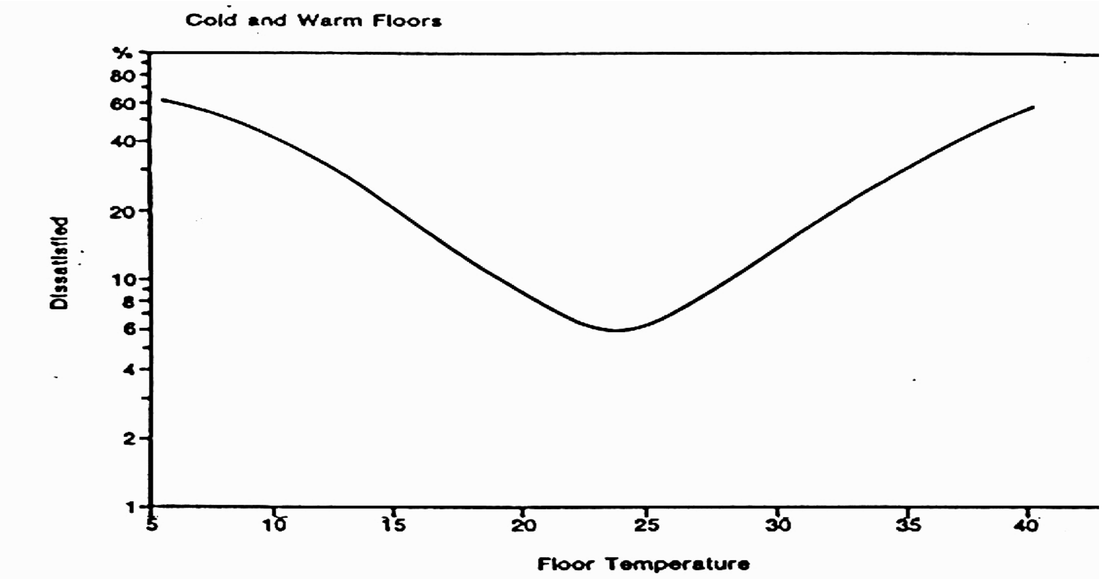
Conclusion:

The radiation asymmetry requirements are more stringent for vertical temperature differences than for temperature differences. Known standards relate to cold windows and heated ceilings. Standards are more lenient for heated walls and floors. Calculations indicate that radiation asymmetry for heated walls and floors is of the same order as for radiator heating. Adverse effects can be prevented by heating large surfaces to a relatively low temperature.

Ratings of emission systems reviewed

radiation asymmetry other planes	**rating**	**remarks**
floor heating	o	Comparable with reference and well within requirements
wall heating	o	Ditto
enlarged radiators	o	Ditto
LT convectors	o	Ditto, effect of building fabric being heated is unknown
LT air heating	o	Ditto, effect of building fabric being heated is unknown

Figure 10: Comfort temperature floors (with foot wear)



2.4. Floor surface temperature

Proposition:

The temperatures of heated floors are higher than those of non-heated floors. So long as the temperature does not become too high, this leads to improved thermal comfort, because heat losses on contact with the floor are much lower. An LT system, if properly designed, prevents complaints such as perspiring feet and fungi growth on feet.

Supporting information:
A cold floor extracts heat from the human body through conduction, resulting in local discomfort such as cold feet. The relevant standards, e.g. NEN ISO 7730 'Moderate Thermal Conditions Indoors' (lit [12]), require that during the heating season the surface temperature of a floor should be between 19 and 26°C and that floor heating systems should be designed for a floor temperature not exceeding 29°C.

Much research has been conducted in order to establish the ideal floor temperature, especially by Olesen in the 1970s and 80s.

Lit [21] reports that the type of flooring material makes little difference as to complaints of cold feet when normal footwear is worn. The optimum floor temperature for a seated person (on a chair, not on the floor) is approx. 25°C (Figure 10, lit [21]). The optimum temperature is 23°C for rooms in which people mostly stand or walk. Figure 8 shows that the PPD is less than 10% for floor temperatures between 19.5 and 28°C.
Thermal conductivity of the flooring material does play a role in rooms where people are barefooted or where the feet are only protected by socks. The optimum floor temperature for such rooms is given in Table 5 (lit [21]. The column in the middle, for a stay for 10 minutes or longer, states the relevant requirements for prolonged usage as in homes. The right-hand column shows the temperature interval for which the percentage dissatisfied is less than 10%.
The optimum floor temperature in rooms where people are barefooted is between 25.5 and 29°C, depending on the flooring material. It is 28/29°C for highly conductive materials such as concrete and marble, and 25/26°C for less conductive materials such as textile and wood.

Table 5: Comfort temperature floors (without foot wear)

Flooring Material	**Optimal Floor Temperature for**		**Recommended Floor Temp. Interval**
	1 min. Occupancy °C	**10 min. Occupancy °C**	
Textiles (mats)	21	24,5	21-28
Cork	24	26	23-28
Pinewood Floor	25	26	22,5-28
Oakwood Floor	26	26	24,5-28
PVC-Sheet with Felt Underlay on Concrete	28	27	25,5-28
Hard Linoleum on Wood	28	26	24-28
5 mm Tesselated Floor on Gas Concrete	29	27	26-28,5
Concrete Floor	28,5	27	26-28,5
Marble	30	29	28-29,5

Table 6: Optimal floor temperature for thermal comfort

Situation	**Optimal temperature**	**10% dissatisfied range**
With foot wear	24 °C	20 - 28 °C
Without foot wear (‘warm’ floor)	26 °C	23 - 29 °C
Without foot wear (‘cold’floor)	28 °C	26 - 30 °C

* warm floor: poor conducting floor covering like carpets, wood
* cold floor: good conducting materials like stone.

Olesen points out that these recommendations apply to the optimal floor temperature for rooms in which people often sit on the floor, such as kindergartens and play rooms.

Bohkagi (lit [28]) arrived at similar temperatures. He tested three conditions which often occur in homes in Japan. In all cases the flooring material was vinyl carpeting:

- A person seated on a chair and wearing footwear (closed slippers);
- A person seated on a chair with only socks on;
- A person seated on the floor and with bare feet.

When the test persons were wearing slippers, thermal comfort was hardly affected by the floor temperature. When they were not wearing slippers or when they sat on the floor, they did feel a significant difference. In this case thermally neutral conditions were achieved at floor temperature of 26 to 28°C (with the air temperature between 18 and 20°C and air velocity being less than 0.10 m/s). Table 6 shows the results of these investigations.

At low outdoor temperatures, the temperature of an unheated groundfloor is usually 15 tom 18°C and only seldom higher than 20°C. Depending on the level of insulation of the dwelling, a heat floor may well be between 21 and 25°C (lit [14] and [18]).

It will be clear, then, that floor heating systems provide optimum thermal comfort in terms of floor temperature. It is definitely recommendable where people often are barefooted or sit on the floor or where the floor is a highly conductive material.

No evidence was found suggesting that high floor temperatures promote bacterial growth on feet.

Figure 11: Influence of floor temperature on growth of micro organism

FLOOR HEATING:	**ON**		**OFF**		**SIGNIF.**
	mean	**SD**	**mean**	**SD**	**$p < 0.05$**
$(cfu_{end} - cfu_{start})$/ml	21.375	21.583	11.500	8.705	-
PMV (start)	0.19	0.740	-0.43	0.480	-
PMV (end)	0.46	0.518	-0.10	0.576	-
local comfort (start)	0.52	0.717	-0.60	0.949	X
local comfort (end)	0.99	0.503	0.29	0.629	X
t_{skin} ankle (start), °C	31.8	2.21	30.4	2.12	-
t_{skin} ankle (end), °C	32.1	1.20	30.9	1.32	X
t_{skin} instep (start), °C	31.9	2.80	30.9	2.31	-
t_{skin} instep (end), °C	32.2	2.08	30.8	1.60	-

Figure 12: Different construction configurations for floor heating

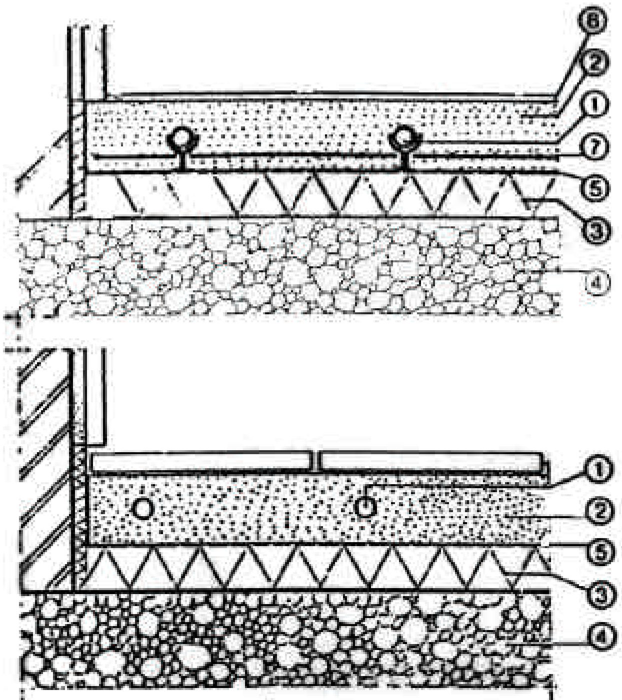


Fig. 1a Buizen in de (cementgebonden)-dekvloer op isolatielaag (nat systeem).

1 vloerverwarmingsbuis
2 (cementgebonden) dekvloer
3 isolatielaag
4 constructievloer
5 waterkerende laag
6 strekmetaal
7 bouw staalmat
8 vloerbedekking cq vloerafwerking

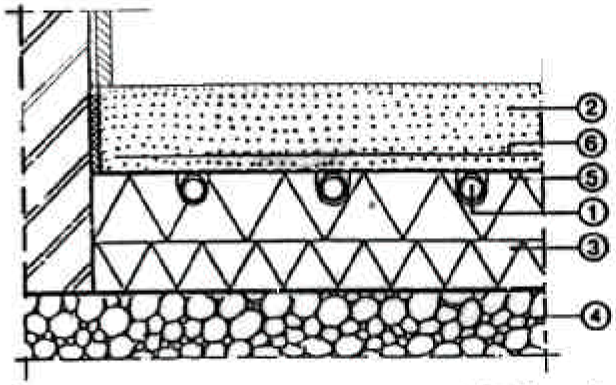


Fig. 1b Buizen in een isolatielaag onder de dekvloer; deze systemen zijn veelal voorzien van niet in de figuur aangegeven warmtespreidende elementen (droog-nat systeem).

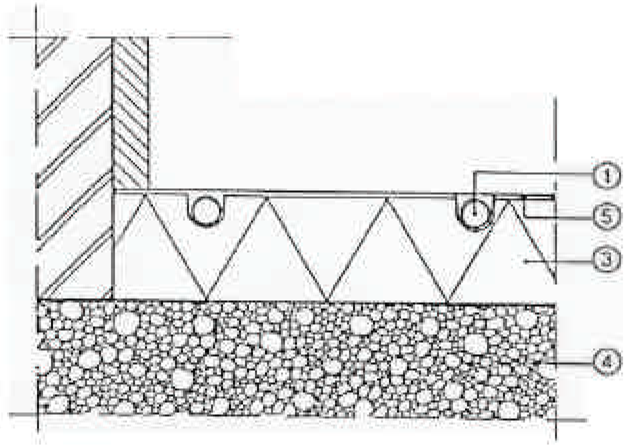


Fig. 1c Buizen in een isolatielaag en de afwerklaag direct op de isolatielaag (droog systeem)

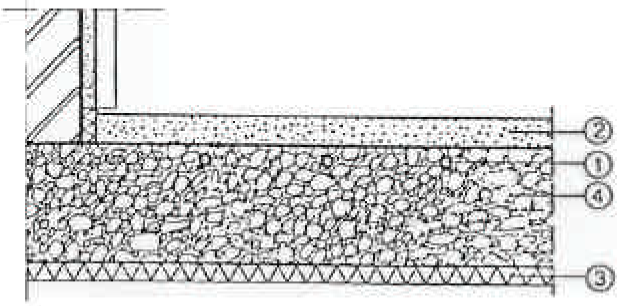


Fig. 1d Buizen opgenomen in de constructievloer.

1 vloerverwarmingsbuis
2 (cementgebonden) dekvloer
3 isolatielaag
4 constructievloer
5 warmtespreidend elemen.

2.6 Temperature fluctuations

Proposition:

A quick temperature fluctuation around an average desired operative temperature has negative influence on thermal comfort. LTH systems are better capable maintaining constant temperature as a result of thermal inertia and larger heat capacity and accumulation

Supporting information:
Indoor temperatures have a cyclic pattern around an average value. According to lit [31] annoyance occurs at quick fluctuations. As a comfort criterion following is found:

$$(\delta T)^2 * f < 4.6$$

where

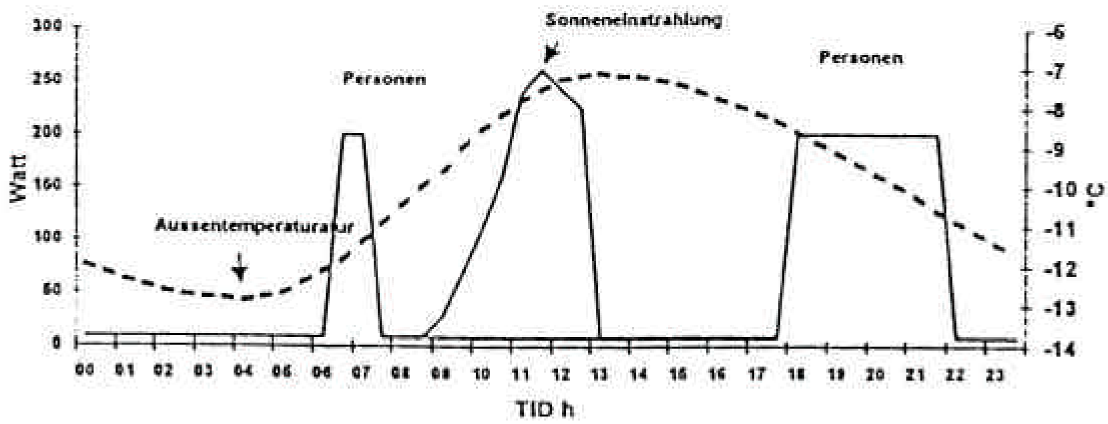
δT difference in minimum and maximum temperature
f number of fluctuations/hour

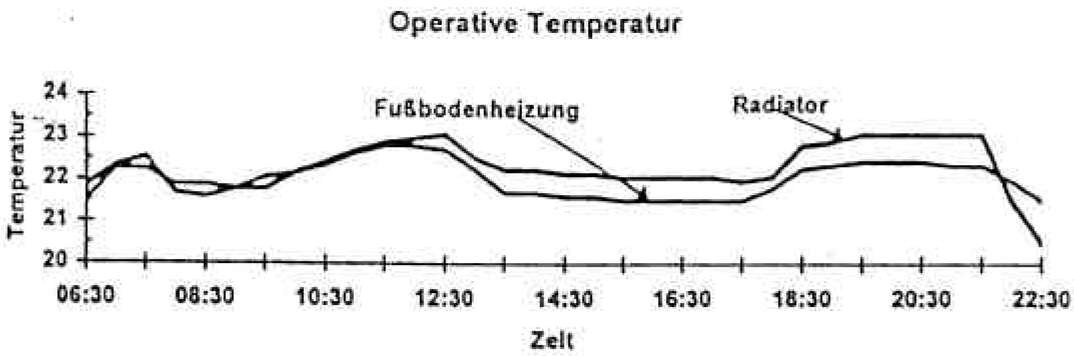
LTH systems are relatively slow because they operate with small temperature differences in combination with a larger co-operating thermal mass. Hence it is expected that quick fluctuations will not occur in floor and wall heating. For LT radiators, convectors and air heating this effect is not so substantially as it is with floor and wall heating. However, the situation is better than with HT systems.

Besides temperature fluctuation caused by the heating system also other effects can occur. This concerns internal heat gains (a user effect of the building) and incident solar radiation. The slowness of a heating system, especially the emission part, can be a disadvantage. This can particularly be a problem with solar radiation as this can have a very fluctuating character. This could lead to a very quick heating up and even overheating of a room. Even for very quick responding systems like air heating it is difficult to react adequately to solar fluctuations (lit [31]). Regular control systems are not suitable to deal with this. Most LTH systems have a self regulating effect. This has a positive effect on the indoor temperature. Olesen reports measurements of these effects in laboratory and in practice (Olesen lit [37], Zolner lit [2], Fort lit[32]). His conclusions are:
– the floor system (in case of floor heating) has limited thermal mass in relation to the rest of the building;
– the positive effect of thermal inertia.

The latter concerns the heat transfer of the emission system to the environment. Small temperature differences between the heating system and the environment lead to large increase/decrease as a result of changes in room temperature. In table 8 (lit [37]) the effect is give for a change of room temperature with 1 K. especially in buildings with a very low heating demand this effect is very large.

Figure 13: Operative temperature with incident solar radiation and internal heat sources





Conclusions:

Quick temperature fluctuations around an average operational (comfort) temperature can lead to discomfort. The biggest fluctuations occur in traditional systems, especially with HT air heating. Control systems are usually not advanced enough to avoid this. LTH systems however have a larger thermal mass to damp this. Beside that the relatively small temperature differences between heating system and environment lead to a much more equal heat demand. Most important effect however is the self regulating effect caused by thermal inertia. This occurs at all LTH systems.

Temperature fluctuation	**Rating**	**Remarks**
Floor heating	++	Large mass and thermal inertia
Wall heating	+	Ditto, with slightly higher temperatures
Enlarged radiators	+	Ditto
LT convectors	+/0	Inertia, limited influence
LT air heating	+/0	Ditto

2.5. Heating and cooling rates

Proposition:

LT heating systems are characterized by low heating and cooling rates. This is a drawback in conjunction with night set-back, window airing and prolonged absence of the occupants. Buildings heat up more quickly and cool down (even) more slowly as their heat losses decrease. An advantage of slow cool-down is that reheating requires less energy.
The thermal mass of LT systems, especially floor and wall heating, is greater than that of HT systems, although this makes only little difference in comparison with the overall thermal mass of buildings.

Supporting information:
Lit [31] recommends that heating and cooling rates should not exceed 0.6 K per hour. In the Netherlands, consumers organizations, (e.g. organisation for consumer guarantees G.I.W), specify higher values, notably for heating, i.e. 4°C per two hours. This is assuming that the temperature drop developing during night set-back or absence is to be restored in two hours (lit [34]).

The literature points out that the thermal mass or heat content of the heating system is an important parameter for heating and cooling rates.

An LT floor heating system is compared here with an HT radiator system so as to gain an understanding of this relationship.

The following key figures relate to a room with a floor area of 50 m^2.

	Floor heating	**HT radiators**
– $T_{supply} – T_{return}$ of medium	10K	20K
– Temperature swing at heat emitting surface	5K	50K
– Assumed emitting area	50 m^2	5 m^2
– Spacing of floor tubing (centre-to-centre)	0.3 m	
– Diameter of tube	22 mm	15 mm
– Capacity of emitting device	0.06 m^3	0.02 m^3
– Specific heat content of medium ($\rho c V_{water}$)	0.3 MJ/K	0.1 MJ/K
– Difference between $T_{mean, medium}$ and T_{room}	10 K	60 K
– Heat content of medium ($\rho c V_{water} * \Delta T$)	3 MJ	6 MJ
– Heat content of floor/steel ($\rho c V_{water} * \Delta T$)	21 MJ	2 MJ
– Total heat content ($\rho c V_{water} * \Delta T$)	24 MJ	8 MJ

Table 7: Time constants for floor heating at different configurations

Type of system	**Mass upper layer**	**Mass construction slab**	**Mass casting**	**Thickness insulation between construction an heating part**	**Time constant**
	kg/m^2	kg/m^2	kg/m^2	mm	hours
1. dry	-	350	50	30	0.2
2. wet	100	350	50	60	1.5
3. wet	160	350	570	60	2.5
4. dry	-	600	570	8	3.0
5. dry-wet	70	600	570	8	6.0
6. wet	140	450	570	60	8.0
7. wet	140	450	570	0	12.2
8.wet	140	600	570	0	13.5

With floor heating, the difference between the medium supply and return temperatures is only half as large as with a traditional HT system. Thus, the flow rates must be twice as large for the same amount of heat to be conveyed.

With HT radiators, the temperature rise at the surface is ten times as large as with floor heating. Thus, the surface area needs to be ten times as large for the same amount of heat to be transferred. This means that the liquid capacity of the floor system must be three times that of HT radiators. Hence, the thermal buffer capacity of the medium is also three times larger.

When the boiler in a HT system is operating, the mean operating temperature is 80°C (60K difference with outside air temperature). The temperature of the floor system is

30°C (10K difference). Both systems cool down when the boiler cuts out. At that point, because of the higher operating temperature, the heat content of the HT system is about twice that of the floor system. If, in addition, the heat contents of the 5 cm cement slab and the metal of the radiators (50 kg) are factored in, then the heat content of the floor system is about three times that of the HT radiators. In a HT system, the surrounding building fabric will also be a contributing factor. Thus, the effective thermal mass of a floor system is about twice that of a HT system.

The same applies to wall heating except that temperatures may be somewhat higher. The heat contents of systems employing LT radiators, convectors and air heaters are comparable with those of their HT counterparts. The lower temperature is compensated for by a larger volume. Little information is available as to whether heating is more rapid with a small emitting surface and a high temperature or with a large area and a low temperature (at equal heating power).
Regarding the relative low temperature differences (in absolute way) regarding radiator and convection transfer this effect seems neglectable.
Lit [9] quotes a number of time constants that were determined in two investigations relating to floor heating (Figure12). The time constant is the time lapsing between boiler switch-off and the point where cooling has progressed to 63%. The mass of the screed and the floor itself were varied depending on the configuration, as were the mass of the surrounding walls and the insulation level. The results are shown in Table 7 (lit [9]). Apparently, the time constant depends more on the mass of the walls than on the screed thickness. With HT systems, especially the mass of the walls will have a contributing effect. This mass typically is 570 kg/m^2 for rooms in homes and office buildings. Lit [9] gives no comparisons for any other systems. It does quote heating and cooling rates from the point where the system is switched on or off. It takes 2.5 to 4.5 hours for the temperature to decrease by two degrees and 15 to 22 hours for the temperature to increase by 2K. It should be noted here that the system is designed for an interior air temperature of 19°C at a floor surface temperature of 29°C. The increase from 18 to 19°C takes extremely long. The first steep section of the heating curve can be used to better effect by designing the system for a higher room temperature.

Table 8: Thermal inertia

Specific heat need	**Floor surface temperature**	**Equalized heating temperature**		**Decrease in heating emission at 1 K increase of room temperature (%)**		
W/m^2	^{0}C	Stone (0.02 m^{2}K/W)	Carpet (0.1 m^{2}K/W)	Floor surface temperature	Equal. Temp. Stone	Equal. Temp. Carpet
80	27.3	31.9	38.4	14	8	5
40	23.9	26.2	29.4	26	16	11
20	22.1	23.3	24.9	48	30	20
10	21.1	21.7	22.5	91	59	40

Today, due to improved insulation and control of ventilation losses, higher heating rates can be achieved even with LT systems. Also, cooling takes longer because of reduced heat losses. Thus, the conclusion is that floor heating does meet the heating and cooling rates referred to in lit [31]. On the other hand, it is well to reconsider whether night set-back is useful at all. Its effect diminishes due to improved energy conservation and improved energy efficiency. When a home is aired, the air temperature initially decreases. This requires only little energy given the limited heat content of the air. If airing is done properly, cooling of the thermal mass is only limited and so has only a limited effect on heating.

A drawback of floor and wall heating in the presence of high amounts of contributing thermal mass is that heating takes place from the inside out. With other systems, the air temperature rises first, followed by that of the building fabric. Consequently, the radiant temperature in the room increases while the building fabric may still be cold. As solid floors and walls are heated, their thermal mass is heated from the inside out, so that it takes longer for their surface temperature to increase.

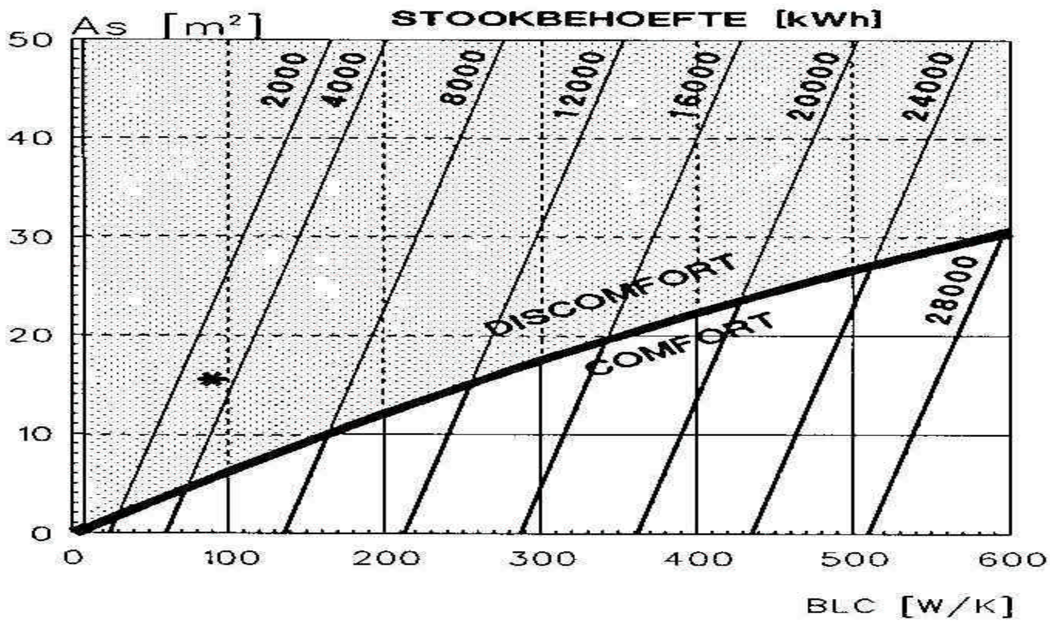
Ratings of emission systems reviewed

Temperature fluctuations	**Rating**	**Notes**
floor heating	-	Large mass; heating from inside; dependent on building construction
wall heating	-	Ditto
enlarged radiators	o	Neutral
LT convectors	o	Neutral
LT air heating	o	Neutral

Table 9: Incident solar radiation for de Bilt the Netherlands (TRY)

Incident solar radiation	**Direct MJ/m^2**	**Diffuse MJ/m^2**	**Total MJ/m^2**	**Relative (%)**
January	0.0	33.3	33.3	1
February	42.2	54.2	96.6	4
March	108.8	112.6	221.4	9
April	124.3	148.8	273.1	12
May	102.1	202.1	304.2	13
June	91.9	222.1	314.1	13
July	81.8	212.6	294.4	13
August	157.9	184.8	342.7	15
September	101.8	129.7	231.4	10
October	77.6	79.5	157.1	7
November	2.9	36.5	39.4	2
December	0.0	26.8	26.8	1
Total	897.1	1442.9	2334.6	100

Figure 14: Energy-comfort diagram



2.6. Overheating

The risk of overheating in summer conditions increases with increasing insulation levels and utilization of passive solar energy. Overheating can be prevented by features such as sunshades, mechanical ventilation and cooling. LTH systems can provide a limited amount of cooling.

Supporting information:
In Western Europe there is a substantial difference in the amount of incident solar radiation between summer and winter. Table 9 shows the monthly total amounts of energy for a vertical plane facing South, based on the hourly figures from the Test Reference Year (TRY) for de Bilt The Netherlands. The TRY is a representative summary of hourly figures developed for a number of locations. In the Netherlands such summaries are distributed by the national meteorological institute. The table shows that in summer, the incident solar radiation on a vertical plane can be as much as 15 times higher than in winter. Two thirds of overall annual solar radiation occur during the five summer months. IEA Assignment 13 ”Advanced Solar Low Energy Buildings” covers a comprehensive investigation into possibilities of utilising (passive) solar energy in winter. Early results indicated that any substantial usage of solar energy during the heating season would lead to overheating in summer unless preventive measures are taken. Table 9 illustrates this. Overheating in low-energy homes can only be avoided by ensuring that the building envelope has different thermal properties in winter and summer.
In IEA Assignment 13 an Energy Comfort curve (Figure 14 (lit [35]) has been derived from numerous calculations. The vertical axis is the open glazed area on vertical South plane A_s. This parameter is a measure of incident solar radiation and includes internal heat sources. The horizontal axis shows the Building Load Coefficient, corresponding with the aggregate transmission and ventilation losses. The curve, constructed by regression analysis, draws the line between a comfortable an uncomfortable interior climate. Annual heating demands are also shown. A lower heating demand can be achieved by lowering the BLC. At the same time, A_s should also be reduced so as to prevent overheating. Both BLC and A_s should be seasonally adjusted. In summer, A_s can be reduced by means of sunshades and BLC can be increased by cavity ventilation. A drawback of these features is that they impose control limitations, e.g. when the occupants are out, and the capacity may be inadequate at high outdoor temperatures. There may also be other objections such as a higher risk of burglary with open windows, noise loaded facades and additional investment.

Table 10: Data for heating and cooling planes

		a W/m^{2}K		Surface temperature °C		Maximal power W/m^2		Total power W	
		Heating	**Cooling**	**Max. heating**	**Min. Cooling**	**Heating**	**Cooling**	**Heating**	**Cooling**
Floor	Edges	11	7	35	20	165	42	3960	1512
	Living zone	11	7	29	20	99	42		
Wall	Facade							864	389
	Back wall	8	8	~40	17	160	72	2592	1166
	Side wall							5184	2333
Ceiling		6	11	~27	17	42	99	1512	3560

The curve relates to a home in an apartment building with standard insulation. Winter conditions are marked by W*, standard summer conditions by Z and doubled ventilation flow rates by Z”. A_s is 11.1 m^2 in summer. Thus, in August the amount of incident solar radiation is 342.7 x 11.1 = 3804 MJ (1057 kWh). This heat can be discharged by an LTH system with cooling mode. Olesen has determined the maximum cooling capacity (lit [14]) needed to achieve thermal comfort. Table 10 indicates a maximum capacity of 42 W/m^2 for floors. For direct incident solar radiation this may be as high as 100 W/m^2 depending on the control system used. If the cooling capacity is 42 W/m^2 and the floor is 60 m^2, all solar heating over the month of August is cooled away in 13.5 hours per day. If the temperature difference is 6K, this requires a flow rate of 0.36 m^3/h. A similar equation may be made for wall heating. Wall cooling involves the risk of

localized cold areas caused by temperature drop near windows. The cooling capacity of LT radiators is limited because of their limited surface area and the absence of direct incident solar radiation.

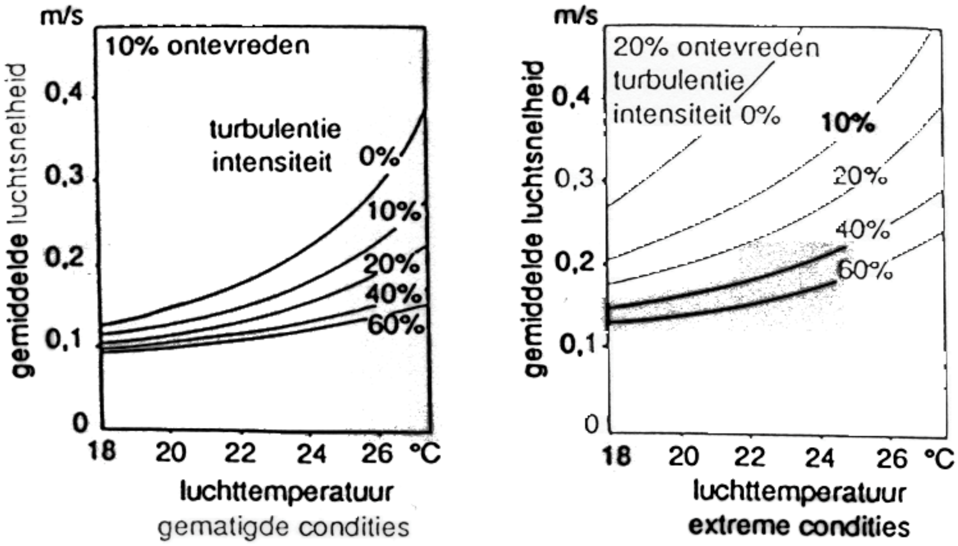
Conclusion:

From a thermal comfort point of view, floor and wall systems are well suited for cooling in summer. Indeed, given a suitable control system (for each room), sunshades and mechanical ventilation may be omitted. Control systems may readily be extended for this purpose. Cooling eliminates the drawbacks of natural ventilation (night ventilation) and sunshades, such as wind nuisance, burglary and noise loaded facades. High cooling capacities (up to 100 W/m^2) can be deployed especially in building elements exposed to solar radiation without impairing comfort or causing condensation problems. Dew point control is essential in such cases. From an energy point of view, the merits of cooling are dependent on the sources used. Systems that include thermal buffering (in the soil or surface water) are particularly suited for low-energy cooling (with or without regeneration of the source).

Ratings of emission systems reviewed

Cooling capability	**Rating**	**Notes**
floor heating	+++	With dew point control
wall heating	++	Greater heat transfer but less sun and surface area
enlarged radiators	o	Depending on source
LT convectors	o	Depending on source
LT air heating	+	Lower risk of condensation

Figure 15: Combinations of average air velocity, air temperature, and turbulence intensity at PPD = 10%



2.7. Air velocity

Proposition:

LTH systems produce lower air velocities due to better distribution over the available area and lower temperature levels. LTH systems are less able to compensate for air currents around cold surfaces and are more critical in respect of draught because of the lower air temperature. Radiators and convectors produce greater air flows but at lower velocities.

Supporting information:
If and to what extent an air current is perceived as draught depends on three parameters (lit [36]):

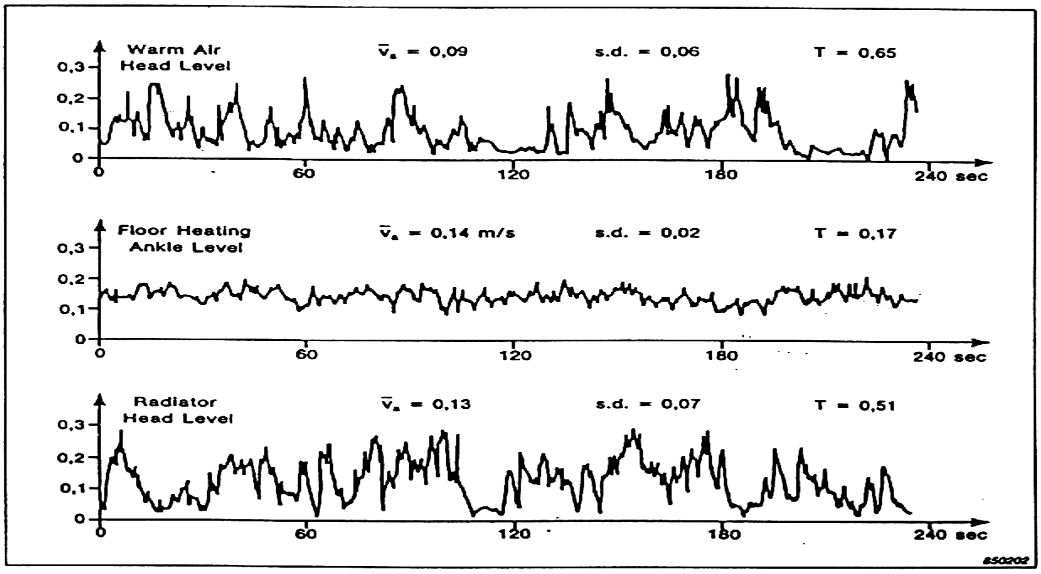
– mean air velocity;
– turbulence (variation from the mean value);
– air temperature.

Figure 15 (lit [36]) shows the combinations of air velocity, air temperature and turbulence at which the predicted percentage dissatisfied is less than 10%. As can be seen, draught increases with lower air temperatures, higher air velocities and higher turbulence. Draught is heavily affected by the type of heating system and the locations of heating elements relative to windows. Other factors are air infiltration and the air-tightness and thermal transmission coefficient of the insulation shell (especially the U value of glazing).

Figure 16 (lit [21]) shows the air velocity profiles for air heating, floor heating and radiator heating in winter conditions. Measurements were taken at ankle height (0.1 m) and at head height for a seated person (1.2 m). While the results indicate that floor heating and radiators produce comparable air velocities, there is a distinct difference in the amounts of turbulence: 20 and 50%, respectively.

With floor heating, the air velocity profile is largely determined by the temperature drop at the windows. Turbulence results here from descending air mixing with convective heat emitted by the floor. Draught is felt especially at ankle height.

Figure 16: Air velocities at different heating systems, measured in laboratory



With radiators, draught occurs especially at head height, where cold air from windows mixes with air ascending from radiators. The air velocity fluctuations are greater than with floor heating.

Normal practice is to prevent the temperature drop at windows by locating heating elements beneath the windows. By that reasoning, wall and floor heating systems ought to be combined with such radiators. The following calculation indicates that this is not necessary, and that it makes no difference where heating elements are located, provided that the insulation is of a high level.

Heiselberg (lit [38]) has studied the relationship between draught and cold windows. He found that the maximum air velocity at a distance of between 0.4 and 2.0 m from the cold plane can be estimated with the following equation:

$$v_{max} = \frac{0.095 * H * (\Theta_0 - \Theta_w)}{(x + 1.32)}$$

where

v_{max}	= maximum air velocity
H	= height of cold plane
Θ_0	= operative temperature
Θ_w	= surface temperature of cold surface
x	= distance to cold surface

Assuming an operative temperature of 22°C, an outdoor temperature of –12°C, a distance to the window of 1 m and the highest air velocity allowed by for example NEN ISO 7730, then the height of glazing at which draught just fails to be induced (without any heating element beneath the window) is as follows:

$$H < (12 * v_{max})^2/U_w$$

For 20% turbulence (which is quite probable for floor heating) and an air temperature of 21°C, it is found that v_{max} = 0.18 m/s. With standard double glazing of U = 3.0 W/m^2.K no draught will occur with glazing heights up to 1.6 m. If glazing of U = 1.5 W/m^2.K is used, the glazing may be as high as 3.0 m (lit [39]).

Table 11: Thermal comfort parameters at 0.1 m from floor, 0.6 m from facade

Floor heating	**Air temperature (^{0}C)**	**Air velocity (m/s)**	**Turbulence intensity (-)**	**PPD (%)**
Switched off	17	0.12	20	10-15
Switched on	21	0.10	25	5

Stockholm Technical University has conducted laboratory tests on air velocities and turbulence in a room provided with floor heating and standard double glazing of about 1.7 m high and U = 3.0(lit [40]). An outdoor temperature of –12°C was simulated and measurements were taken at ankle height (0.1 m) at 0.6 m from the wall. Some of the results are presented in Table 11 (lit [40]).

After the floor heating was switched on, the temperature at ankle height was seen to increase dramatically. The air velocity decreased a little and turbulence increased somewhat. The number of experimental subjects that felt a draught was significantly lower when the floor heating was on. The author's conclusion is that floor heating can prevent draught at ankle height otherwise induced by the temperature drop at windows. In an earlier investigation, the same author concluded that such draught occurs less often in homes with floor heating than in homes with radiator or heating (lit [41]).

Lit [42] states that, where floor heating is used, a minor temperature drop occurs in the vicinity of windows, and that this temperature drop is smaller than in the case of radiators and air heating. It can be avoided by suitable siting of the heating elements *or* by using double-glazing. Heating systems and related temperature drops are shown in Figure 17 (lit [42]).

No data were found the literature on any typical air velocity and turbulence figures for wall heating. Theoretical considerations suggest that the air velocities should be somewhat higher and that turbulence should be comparable. Also, draught at ankle height due to cold air from windows is more likely to be a problem.

Conclusion:

With radiator heating, the air velocities in the occupied zone are comparable with those arising with floor heating (and probably also those arising with wall heating).
Also, radiators cause significantly more turbulence. Thus, radiators pose a higher risk of draught. The air velocities for wall and floor heating depend on the temperature drop at windows and the like and can be prevented by thermally insulating glazing (preferably $U_{window} < 2.0$ U/m^{2}K). Standard double-glazing suffices for LTH systems provided the windows are not too high.

Figure 17: Cold drop in relation to heating systems (without influence ventilation)

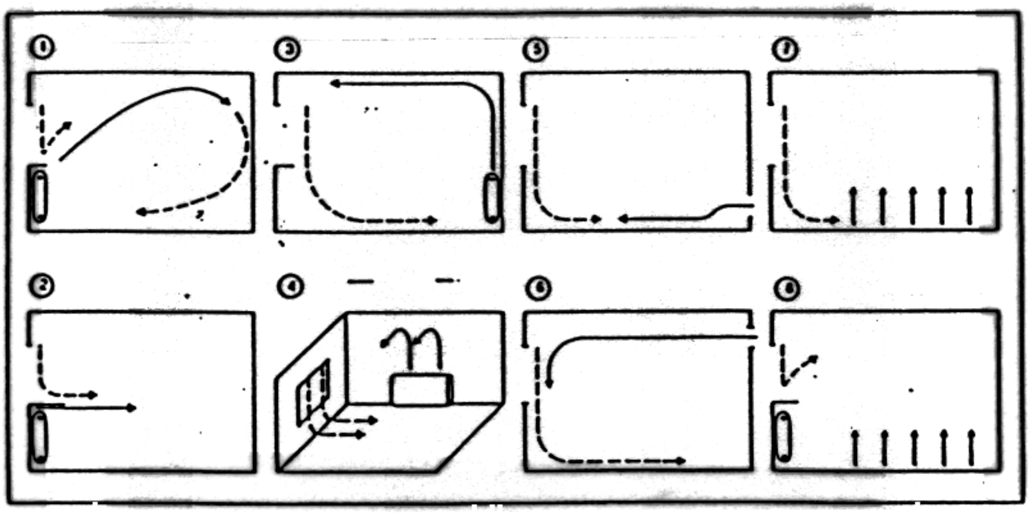


Figure 18: Example RH calculation for moderate climate (de Bilt)

An example of relative humidity calculations (RH in %) for the Dutch town of De Bilt, using prevailing monthly mean temperatures (in °C) and absolute air humidities (AH in g water vapor/m³ air)[17,51,103]. It is assumed that no moisture penetrates the building envelope from the outside.

Compartment studied	Variate	Mean level in: January	July
Outdoor	Temperature	2	17
	AH	5	11
	RH	95	75
Indoor: room air	AH	7	11.5
	RH at 18 °C air temperature	45	75
	RH at 21 °C air temperature	40	65
Indoor: beds and upholstery (in use)	AH	14	16.5
	RH at rim, at 18 °C air temperature	90	condensation
	RH at rim, at 21 °C air temperature	75	90
	Temperature at skin of user	32	32
	RH near user	40	50
Indoor: floors	Temperature at 18 °C air temperature	16	16
	Temperature at 21 °C air temperature	19	19
	AH	7	11.5
	RH at 18 °C air temperature	50	85
	RH at 21 °C air temperature	45	70

Table 12: Characteristic indoor and outdoor humidities in moderate climates

	Indoor			Outdoor			
	Ti	**Pi**	**RVi**	**Te**	**Pe**	**RVe**	**Ce**
per.	[°C]	[N/m²]	[%]	[°C]	[N/m²]	[%]	[g/m³]
1.	20.0	1483.0	63%	12.6	1200.0	82%	9.09
2.	20.0	1333.0	57%	9.7	1067.0	89%	8.17
3.	20.0	1267.0	54%	7.9	967.0	91%	7.45
4.	20.0	1200.0	51%	6.2	883.0	93%	6.85
5.	20.0	1120.0	48%	4.3	800.0	96%	6.24
6.	20.0	1120.0	48%	3.1	717.0	94%	5.62
7.	20.0	1100.0	47%	2.2	667.0	93%	5.25
8.	20.0	1100.0	47%	1.5	633.0	93%	4.99
9.	20.0	1080.0	46%	1.5	617.0	91%	4.87
10.	20.0	1080.0	46%	1.5	633.0	93%	4.99
11.	20.0	1100.0	47%	1.9	633.0	90%	4.98
12.	20.0	1100.0	47%	4.6	717.0	85%	5.59
13.	20.0	1120.0	48%	6.2	783.0	83%	6.07
14.	20.0	1120.0	48%	9.0	867.0	76%	6.65
15.	20.0	1200.0	51%	11.3	967.0	72%	7.36
16.	20.0	1283.0	55%	13.6	1083.0	70%	8.18
17.	20.0	1383.0	59%	15.5	1200.0	68%	9.00
18.	20.0	1500.0	64%	17.3	1317.0	67%	9.82
19.	20.0	1600.0	68%	18.5	1433.0	67%	10.64
20.	20.0	1700.0	73%	19.1	1533.0	69%	11.36
21.	20.0	1750.0	75%	19.9	1558.0	67%	11.51
22.	20.0	1758.0	75%	19.0	1558.0	71%	11.55
23.	20.0	1733.0	74%	18.2	1500.0	72%	11.15
24.	20.0	1617.0	69%	16.2	1367.0	74%	10.23
25.	20.0	1483.0	63%	12.6	1200.0	82%	9.09

2.8. Relative humidity

Proposition:

The RV in many buildings is too low during the heating season, especially during extremely low outdoor temperatures. With LTH system, because of the lower air temperature, the RH is higher than with traditional heating systems.

Supporting information:
The relative humidity of inside air should be in the 30 – 70% range for good thermal comfort (lit [12]). Lit [31] recommends a lower limit of 40 to 45% in order to prevent electrostatic shocks.

Table 12 shows typical RH figures for inside and outside air divided into two weekly periods (lit [43]). As can be seen, the minimum RH at an indoor air temperature of 20°C is 46% on average over a period of two weeks. The corresponding absolute humidity is 8 g/m^3. A 1°C temperature rise results in a 3% decrease in RH. Thus, with an LTH system, the air humidity during the heating season will be 3 to 5 % higher on average due to the lower air temperature.

The differences in absolute terms can be much higher. Lit [44] indicates that moisture production in a home amounts to 7.5 to 15 kg/day. Only 15% is produced overnight by breathing while asleep and by plants. Thus, the air humidity is lowest in the morning. With HTH systems, the home is heated up rapidly in the morning, causing the RH to decrease. Lit [45] says that in winter the humidity in homes ranges from 6 to 8 g/m^3. At 22°C, this corresponds with a RH of 30%. Lit [19] indicates that momentary air temperature differences can be as high as 3°C. An air temperature of 19°C in combination with an absolute humidity of 6 g/m^3 corresponds with a relative humidity of 36%. Given that LTH systems heat up less rapidly and that night set-back has a lesser effect, the RH variations will be more uniform.

Less moisture evolves in offices and public buildings, especially overnight. Consequently, there is a higher risk here of the RH being too low as the building is heated up. Lit [46] reports that 43 % of complaints are to do with dry air in offices.

The lower air temperature which is typical of LTH systems results in a higher relative humidity at equal absolute humidity. The RH can be 3 to 5% higher relative to a mean value of 46%. This effect is greater when the building is heated up. Serious thermal discomfort, with RH < 30%, does not occur in homes with traditional heating systems and so not credit can go to LTH systems for preventing such discomfort. LTH systems do exhibit smaller RH fluctuations and reduce static charging.

Rating of emission systems

Relative humidity	**rating**	**notes**
floor heating	+/0	Especially during heating up and in public buildings
wall heating	+/0	Ditto
enlarged radiators	+/0	Ditto
LT convectors	0	neutral relative to HT systems
LT air heating	0	neutral relative to HT systems

Table 13: Overall satisfaction thermal comfort living room cold winter-conditions

Heating system	Very satisfied and satisfied (%)
Radiator heating	62
Air heating without heat recovery	39
Air heating with heat recovery	60
Floor heating	80

Table 14: Thermal comfort in living room cold winter conditions

Heating system	Good	Too warm	Too cold	Not equal
Radiator heating	63	0	29	0
Air heating without heat recovery	50	0	25	11
Air heating with heat recovery	47	0	16	9
Floor heating	60	0	0	0

2.9. Occupants' appreciation

Proposition:

The climate in buildings heated with LTH systems such as wall and floor heating is generally felt to be comfortable and agreeable. Only scarce information is available regarding LT radiators and convectors. There is no appreciable difference between LT air heating and HT systems.

Supporting information:
Field tests in the Westenholte and Ecolonia projects in the Netherlands included a comprehensive evaluation of the occupants' appreciation of various heating systems.

The Westenholte project (lit [47]) , at Zwolle, was carried out by TNO (Organisation for Applied Physics). The project covered:
- 31 homes with radiator heating;
- 36 homes with air heating without heat recovery;
- 32 homes with air heating and with heat recovery;
- 5 homes with floor heating on the ground floor and radiators on the first floor.

All homes were relatively small and essentially identical single-family homes of 225 m^3. They are fairly well insulated (mean U value of 0.54 $W/m^2.K$ and an insulation index It of 15.5; thermoplus glazing is used on the ground floor). All homes have a mechanical ventilation system. All occupants are much the same age and clothe much the same way. They were interviewed to ask their experience when the mean outdoor temperature over a 24-hour period was subzero. Table 13 (lit [47]) indicates that, on the whole, the occupants are satisfied with the interior climate. Table 14 gives further details on thermal comfort in the living room.

The homes with floor heating received the highest ratings in terms of thermal comfort and overall satisfaction with the interior climate.

Ecolonia (Alphen aan de Rijn, The Netherlands) (lit [48]) is a demonstration project comprising 101 environment friendly homes. Built in 1992, the district includes nine clusters of homes, each of which was designed by a different architect. Each architect worked out a specific environmental theme such as integrated life cycle management, health and safety and bio-ecological construction. Since the project was to set an example, various evaluations were made on its completion . After the first two winters, as assessment was made of the air quality, thermal comfort and energy consumption. Erasmus University of Rotterdam (lit [49]) evaluated the occupants' experience and observations. The results are summarised in Table 15 (lit [48]).

Table 15: Occupants evaluation Ecolonia demonstration project the Netherlands.

Heating type	**(very) satisfied with indoor climate**	**(very) satisfied with heating system ***
wall heating	100 %	88 %
floor heating + radiators	92 %	57 %
floor heating + radiators	91 %	57 %
radiator heating	100 %	63 %
radiator heating	90 %	63 %
radiator heating	82 %	63 %
radiator heating	77 %	63 %
2 zone air heating (indirect heated)	100 %	60 %
2 zone air heating (direct heated)	37 %	13 %

* there are only average values for separate categories (e.g. radiators) available.

Wall heating clearly scores highest in terms of both thermal comfort and satisfaction with the heating system. There are only small differences in appreciation for floor heating (with radiators), radiator heating and *indirectly fired* air heating. The ratings for *directly fired* air heating are significantly lower.

Conclusion:

Two recent, comprehensive evaluations confirm that wall and floor heating systems are highly appreciated by the occupants. This is due to the comparatively high proportion of radiant heat and other comfort-related aspects such as their favourable effect on draughtiness, vertical temperature differences, higher floor temperature and lower air temperature, which makes for fresher air. Satisfaction with the heating system denies supposed drawbacks such as low heating rates and poor controllability. Reliability of operation weighed heavily in the ratings.

Rating of emission systems:

Occupants' appreciation	**rating**	**Notes**
floor heating	++	Especially with stone floors
wall heating	++	Overall perception
enlarged radiators	no lit.	not known
LT convectors	no lit.	effect of larger air currents not known, less turbulence probably positive effect
LT air heating	0	neutral relative to HT systems

3. Air quality

3.1. Airborne particles

Proposition:

A relatively high surface temperature of the heating element causes local high air velocities which are capable of conveying more and heavier particles than low air velocities. Consequently, airborne dust concentrations are lower with LTH systems such as floor and wall heating. Air currents produced by LT radiators and convectors are larger but less turbulent.

Supporting information:
Dust is a collective term for solid and liquid particles dispersed in air, also known as aerosols. Respirable dust is important from a health point of view. This consists of particles smaller than 10 micrometres. Particles larger than 10 micrometres (also known as PM_{10}) are retained in the nose and the oral cavity and do not therefore enter the respiratory tract.

Dust comprises a variety of materials which may be of biological origin, e.g. mite faeces, fungi or fungal traces, bacteria, pollen (from indoor or outdoor plants) and hair from animals. Other particles may evolve from smoking, cooking, combustion, sweeping and vacuum-cleaning (lit [50]).
Dust often consists of particles adhering to each other as a result of static charging. Static charging of the individual particles is dependent on the relative humidity. At high relative humidity, the charge may be dissipated through the air. Conversely, at low relative humidity, the electrostatic pull between particles is larger, resulting in a higher mean particle size.
Other forces that affect deposition and buoyancy are the force of gravity, thermal forces (e.g. rising air currents) and molecular forces as well as air velocity, turbulence and activities such as vacuuming.

Sammaljarvi (lit [75]) investigated the health effects of interior climates during the coldest months in Finland for the following conditions:
- outdoor temperature -20 to -30°C;
- indoor relative humidity 15 to 30%;
- indoor temperature 21°C.

This epidemiological investigation covered a random selection of 6900 adults and 1700 children. The respondents completed questionnaires giving details of their health and well-being and physical data of the home and interior climate.

The results indicated that neurological complaints such as headache, fatigue and inability to concentrate can be attributed to stuffy air and *visible* dust on floors and the like.

Complaints of sinusitis, inflammation of the middle ear and throat infection also occurred especially in homes with large amounts of visible dust.

The incidence of eye complaints (irritation) was lowest in the absence of visible dust and where low surface temperature heating elements are used.

Low air turbulence typical of LTH systems probably has a favorable effect on dust exposure in quantitative terms. We found only one study on this subject; it states that air velocities below 0.10 m/s in combination with low turbulence lead to higher dust deposition rates on walls and floors and so less airborne dust. Conversely, the concentration of airborne dust increases with increasing turbulence.

Conclusion:

LTH systems produce lower air velocities and turbulence than traditional heating systems. Little information was found on the effects on dust deposits and airborne dust concentrations. It is reported that lower heating temperatures reduce health complaints as well as airborne dust concentrations. LT air heating probably is not much different from HT systems in this respect.

Rating of emission systems

Airborne particles	**rating**	**Notes**
floor heating	+++	Lower air velocities and fluctuations
wall heating	++	Ditto, but higher temperatures
enlarged radiators	+	Ditto
LT convectors	+	Ditto
LT air heating	0	neutral relative to HT systems

3.2. Mites

Proposition:

Floor heating causes a higher temperature in the interfacial layer between the indoor air and the floor, resulting in lower local relative humidities. These are adverse conditions for house dust mites. The same applies to wall heating albeit to a lesser extent.

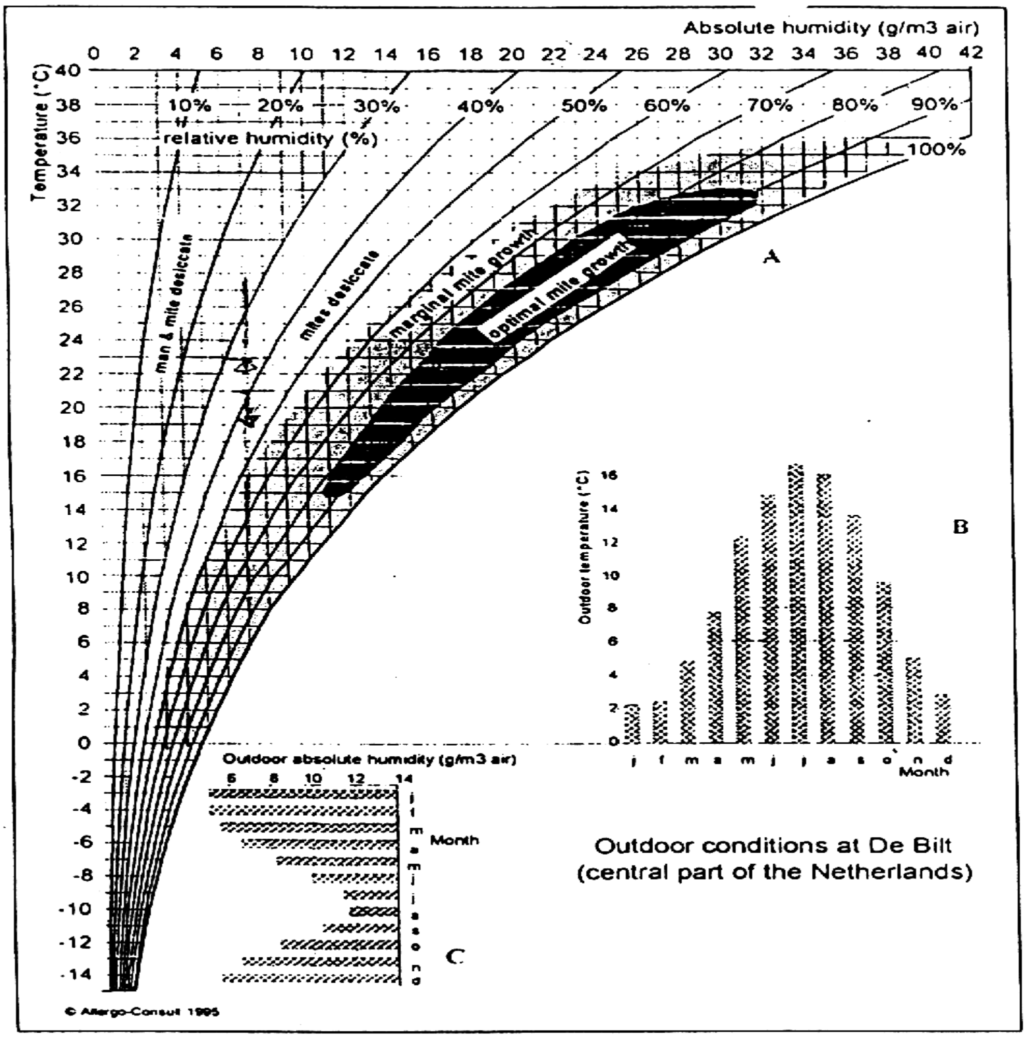
Supporting information:
Van Bronswijk (lit [53]) estimates that 20 to 40% of the population is sensitive to allergens. This means that allergies occur in one out of two households. Indoor exposure is an important factor here depending on the duration of exposure and susceptibility (elderly and infants). Most allergic reactions in buildings are due to contact with faeces of house dust mites.

A Danish investigation (lit [54]) suggests that the incidence of allergies can be halved by reducing exposure to mites in dwellings.

The number of mites, and so the number of their faces, in homes varies with the seasons. A dramatic increase can be seen in spring due to rising temperatures and, more importantly, higher relative humidity. In warm and humid summer conditions, mite population can be 50 to 100 times as large as in winter.
Tests (lit [55]) have shown that seasonal dependence of the indoor mite population is related to variation of the relative humidity. Mites can survive low relative humidities in winter only if they find suitable biotopes such as mattresses or textile flooring materials. This is caused by local occurring higher relative humidities (i.e. hygroscopic properties of materials, local moisture supply by sweat).

Mites cannot survive if the relative humidity *within* their ecosystem (mattresses, carpets, chair upholstery) is less than 45%. This is referred to as the mite survival threshold. Significant reproduction can only occur at a relative humidity within the biotope higher than 60%. The adjusted Mollier diagram in Figure 19 (lit [56]) shows the area in which temperature and absolute humidity affect mite growth. Lit. [57] points out that, if three winters with dry interior conditions occur in a row (with RH in the mite's ecosystem less than 45% for prolonged periods), then the interior materials, especially flooring material, make no difference in terms of mite population. This indicates that it is possible to create a dust mite-low home, indepant of the type of furnishing, mattresses etc.

Figure 19: Relation humidity, air temperature and house dust mites



The difference between radiator heating and floor heating is illustrated by the following example calculation, which is partly based on lit. [56]:

The starting point is an outdoor temperature of 2°C; this is the mean outdoor temperature for January. The outdoor absolute humidity is about 5 g/kg, corresponding with an indoor relative humidity of 95%. The indoor absolute humidity is 7 g/kg (2 g/kg higher than outdoors because of interior moisture production).

Case 1: A dwelling with a normal level of insulation (R_c value for ground floor at least 2.5 m^2.K/W) with radiator heating. RH at an indoor air temperature of 21°C is 40% (Fig. 19, lit [56]). In these conditions the temperature of the ground floor will be about 19°C. The RH in the interfacial layer (carpet) then is 45%.

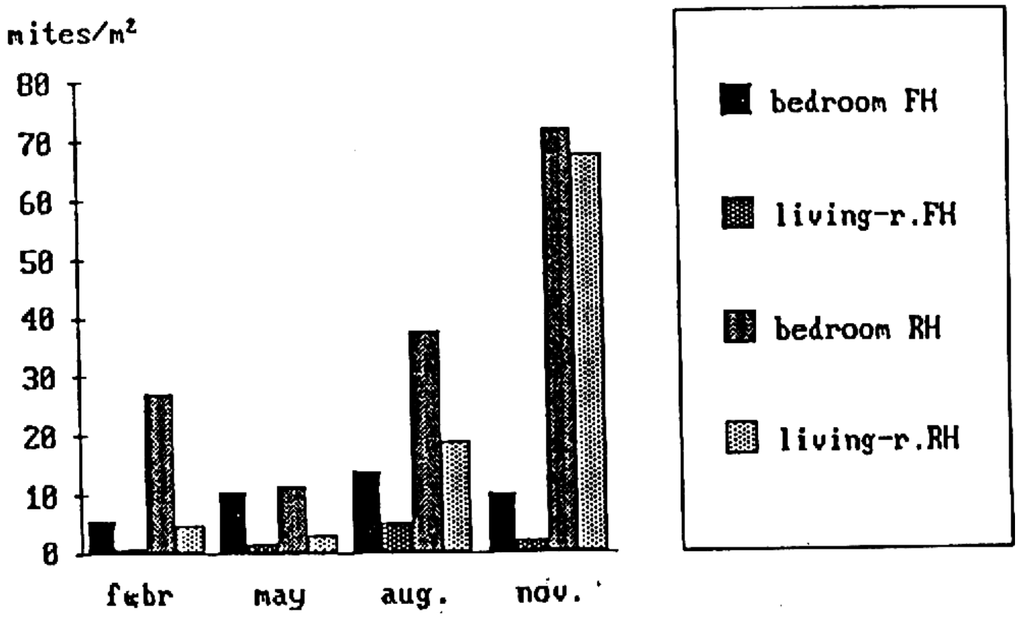
Case II: Similar dwelling except with floor heating. Comparable thermal comfort is assumed to be achieved at an air temperature which is 2°C lower (assumed floor temperature: 24°C). If the indoor air temperature is 19°C and the absolute humidity is 7 g/kg, the indoor RH is 45%. Since the floor temperature is significantly higher, i.e. 24°C in place of 19°C, the RH in the carpet is 30-35%.

This calculation shows that during winter the relative humidity in carpeting on the ground floor is 10% lower with floor heating than with radiator heating. More specifically, the RH is just outside the survivability range for mites. Thus, mites will not survive in winter.

The above results are corroborated by field tests and epidemiological investigation.

Schata et al. (lit [55]) investigated mite populations in textile flooring materials and mattresses in 21 households. Ten had radiator heating and the other eleven had floor heating. Dust samples were taken over a one-year period and analysed for live mites. Samples were taken from carpets in the living rooms and bedrooms and from mattresses. The results are shown in Figure 20 (lit [55]). FH stands for floor heating and RH for radiator heating.

Figure 20: Season-depending concentration mites in carpets (floor heating and radiators)



During the heating season, the number of mites in dwellings with radiator heating is 5 to 30 times higher than in dwellings with floor heating. The type of heating is immaterial by the end of spring (May). The heating system used in bedrooms makes less difference than those used in the living rooms, probably because bedrooms are heated to a lesser extent.
A remarkable difference was found regarding the numbers of mites in the mattresses during winter (not shown). With radiator heating, mite concentrations averaged 470 per m^2 and with floor heating only 34 per m^2, a factor of almost 15.

The findings of Schata et al. (lit [55]) are in agreement with those arrived at by others.

Kuehr et al (lit [58]) conducted an epidemiological investigation in the households of 1291 school children aimed at identifying conditions conducive to asthma and allergies among children. Another object was to establish what factors might lead to increased mite concentrations in mattresses. An inventory was made of relevant factors such as the type of heating system, damp patches on the walls, year of construction, number of occupants, and the presence of pets. Measurements were taken between December and April. Dust samples were taken from the children's mattresses and the air humidities and temperatures in bedrooms were measured.
The results indicate that absolute high air humidity and low air temperature promote mite growth in mattresses. Complaints of allergies often went hand in hand with damp problems. Here again mite concentrations were smaller in dwellings with floor heating. The authors recommend that allergies and asthmatics should not sleep in the basement or on the ground floor and should avoid rooms with visible damp patches and that they should use floor heating if possible at all.

Ekstrand-Tobin (lit [59]) arrived at similar results. An investigation covering 60 dwellings in which young asthmatics lived showed that patients living in floor-heated homes were significantly less likely to be allergic to dust mites than those living in homes with different heating systems. Kort et al. (lit [60]) and Leupen (lit [61]) arrived at the same conclusion: Floor heating reduces the relative humidity in the interfacial layer between inside air and the floor, inhibiting mite growth.

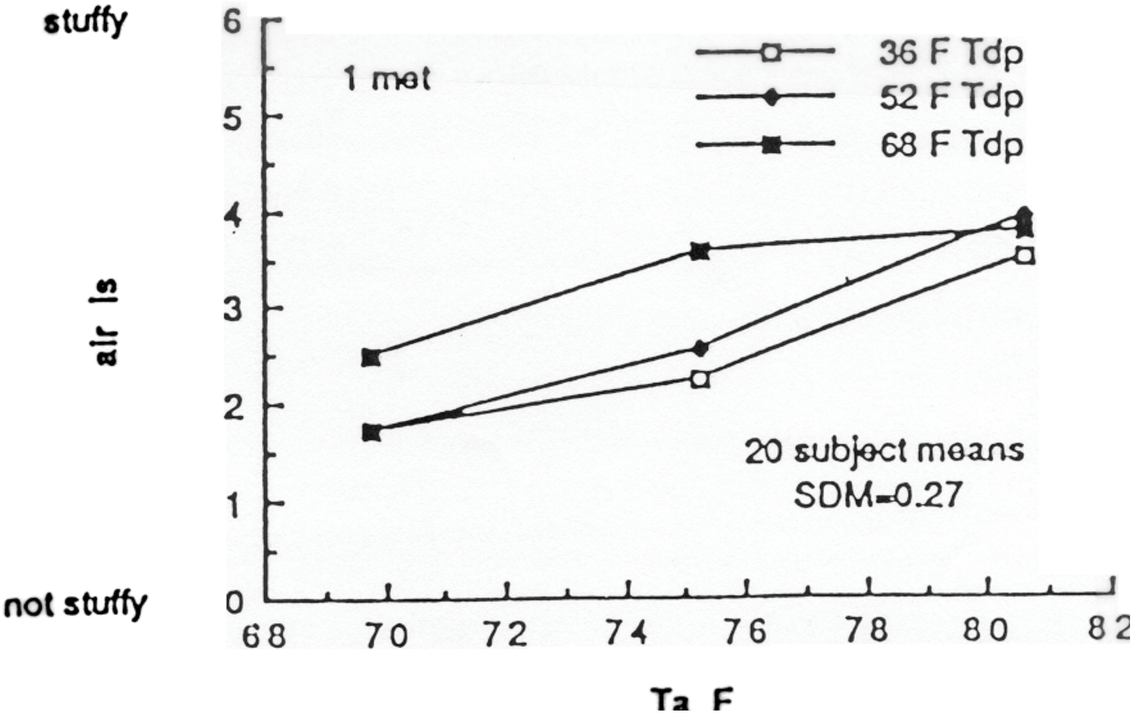
Conclusion:

Studies indicate that there is a distinct relationship between floor temperature and mite growth. A high floor temperature in combination with low RH in the interfacial layer makes for low, if any, mite growth. The relative high surface temperature of the floor is dominant, it makes no difference here whether the heat source of the floor heating system is a HT or LT one. Therefor it is expected that for other LT emissions systems there will be no difference with traditional HT systems

Rating of emission systems

Mite growth	rating	notes
floor heating	+++	Smaller populations due to lower local RH
wall heating	+	Higher proportion of radiant heat
enlarged radiators	0	Neutral relative to HT system
LT convectors	0	Ditto
LT air heating	0	Ditto

Figure 21: Rating stuffiness air



3.3. Enthalpy

Proposition:

Wall and floor heating systems create a thermally neutral environment with lower air temperatures than traditional systems. Low air temperatures prevent building-related health complaints such as irritation of the eyes and the respiratory tract and make for more favourable sensory perception of inside air (contaminated air smells less unpleasant according as the air is cooler and drier). This probably holds to a lesser extent for enlarged radiators. No difference was found between LT convectors, air heating and HT systems.

Supporting information:
Bedford (lit [62]) states that warm wall environments, which because of the high proportion of radiant heat have a low air temperature, are perceived as fresher and more comfortable than warm air environments. The latter reportedly cause blockage of the nose.

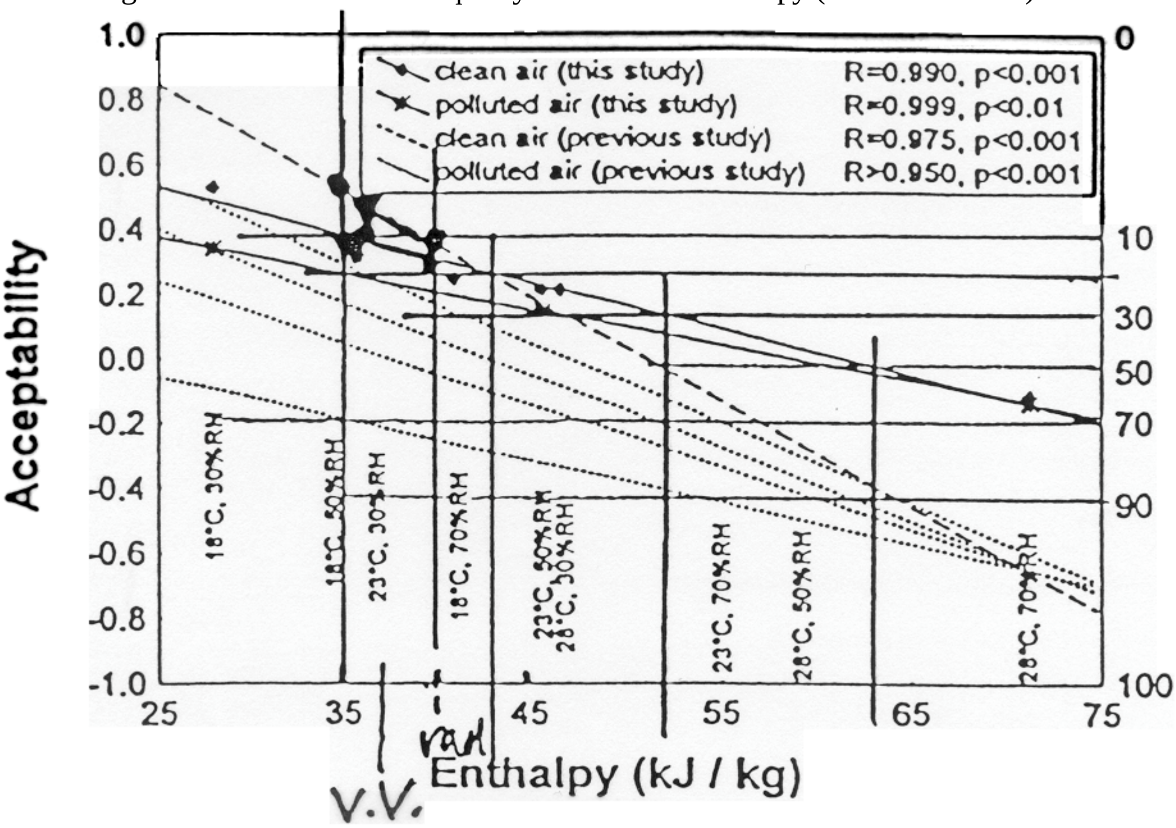
The effects of air temperature and humidity on perceived air quality have been studied by Berglund & Cain (lit [64]) in a controlled environment. The level of work performed by the subjects was varied between 1 Met (seated and hardly any activity) and 3 Met (comparable to walking at 5 km/h). Figure 21 (lit [64]) shows how stuffiness of the air was assessed at a level of work of 1 Met. The air temperature was varied between 20 and 27°C and air humidity was adjusted to 5, 8 and 15 g/kg with corresponding dew point temperatures of 2, 11 and 20°C.

The inside air was felt to be fresher and less stuffy as the temperature and humidity decreased, the effect of temperature being the larger. The relationship between air temperature and perceived air quality proved more or less linear.

An investigation covering 23 office buildings in the U.S.A. (lit [63]) also revealed a distinct relationship between air temperature and perceived air quality. A total of 228 respondents were asked to rate the air quality on a scale from -3 (very stuffy) to +3 (very fresh). Particular attention was paid to the effects of air temperature, humidity, air velocity and fresh air supply.

The effect of air temperature was found to be large. After the air temperature was reduced by 2.4°C, the rating was a full point higher. The linear relationship yields the following ratings:
– at 19°C neutral (rating: 0);
– at 21.5°C somewhat stuffy (rating: +1);
– at 25°C fairly stuffy (rating: +2);
– at 27.5°C very stuffy (rating: +3).

Figure 22: Perceived air quality as function of enthalpy (extended version)



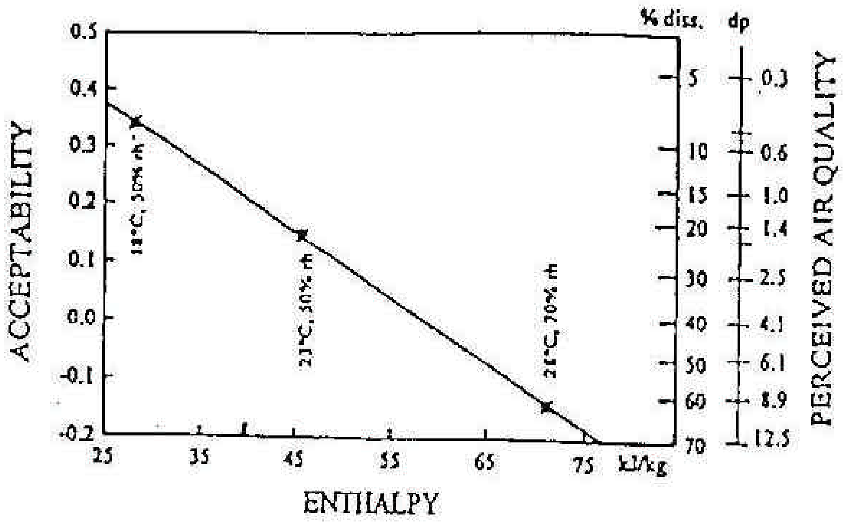
The effects of the other parameters were less profound. The relative air humidity, in all cases between 44% and 60%, hardly affected the perceived air quality. The effect of air velocity was also only marginal. That of fresh air supply was much less than anticipated. Tripling the air supply rate resulted in a rating only one point higher on the scale.

These findings are corroborated in recent studies by Fang & Fanger (lit [55] and [56]), who investigated how clean air and air contaminated with building material and interior appointment material (which often occur in the built environment) are appreciated. The temperature was varied between 18, 23 and 28°C and the relative humidity between 30, 50 and 70%. The subjects were asked to assess the air quality immediately on entering the room and after twenty minutes.
The authors conclude that temperature and relative humidity have a profound effect on the perceived air quality. At 18°C and 30% the percentage dissatisfied was only 10%. At 28°C and 50%, the percentage dissatisfied was 60% (the air composition being unchanged). Here again, the relationship between the air enthalpy and perceived air quality is linear; see Figure 22 (lit [65]). Figure 23 (lit [67]) is a simplified representation of the relationship found. A similar linear relationship was found by Berglund & Cain (lit [64]).

Various epidemiological investigations indicate that there is also a relation between the mean air temperature and sick building symptoms. For one thing, the incidence of irritation of the eyes, trachea and bronchial tubes increases with increasing air temperature.

Skov & Valbjorn investigated 36 office rooms in four town halls in Denmark. Their measurements included the air temperature and relative humidity, and the concentrations of dust, ozone, formaldehyde and carbon dioxide and the number of air changes. The occupants were asked if they had any complaints regarding the indoor environment and building-related symptoms. The investigation was carried out in winter and the indoor temperature ranged from 19.9 to 24.3°C.
Statistical analysis of the results revealed a relationship between the number of symptoms and the degree of cleanliness and air temperature in the buildings. The incidence of sick building syndrome tripled on increasing the air temperature by 3°C. Therefore, the authors recommended that during winter the indoor air temperature should be not (much) higher than 21°C.

Figure 23: Perceived air quality as function of enthalpy (simplified version)



The results obtained in the Danish town halls correspond with those of Jaakkola (lit [69]). Epidemiological investigations in offices and dwellings in Finland indicated that the air temperature is the prime factor in the development of sick building complaints. Complaints of dry air, too, result from high air temperatures rather than low humidity. (Others, e.g. Sundell (lit [70]), also found that complaints of dry air are not so much to do with air humidity as with airborne pollutants and high air temperatures.

Summarizing, there is ample evidence that high air temperatures (>21°C) are the cause of building-related health complaints and negative sensory sensation such as odour nuisance. Various studies attempt to identify the root cause:

- At lower air temperatures, the relative air humidity and the moisture content of aerosols are higher. This enables the natural ion balance to be restored. A disturbed ion balance may cause irritation of the respiratory tract and other health complaints (lit [5] / original source: Samaljarvi (198); lit [78];
- A higher air temperature increases emissions from building materials and furniture. Emissions from fresh paint coats and new carpeting may cause odour nuisance and health complaints especially for the first few weeks (lit [71]);
- A higher temperature increases the reactivity of chemical substances, accelerating reactions. A case in point in offices is the reaction between ozone from copying machines and organic solvents from carpeting to form aldehydes including formaldehyde. Extremely low concentrations of such substances can cause irritation (lit [72]).The aforementioned reaction proceeds more rapidly at higher temperatures (lit [73]);
- Colder breathing air is perceived to be fresher than warm air. It is preheated and moistened in the nose and throat and is about 32°C and has a RH of almost 100% by the time it enters the lungs. Breathing probably is more agreeable if the air is cooler and drier. A similar effect can be observed with beverages; lukewarm water and beer are not normally felt to taste good (lit [67]).

Conclusion:

LTH systems such as floor and wall heating produce a comparatively large proportion of radiant heat. As a result, the same level of comfort can be achieved at a lower air temperature, which is advantageous in terms of enthalpy. Various studies indicate that cool air is appreciated more than warm air. The relationship with air temperature is a linear one. Other parameters such as air velocity, RH and even replacement have a distinct effect on the level of appreciation. High air temperatures, especially those higher than 24°C, lead to more complaints such as stuffiness and sick building syndrome. The same effects may occur with enlarged radiators. No differences were found between LT air heating and LT convectors and the reference system. In the case of air heating in conjunction with heat recovery it is also possible for cold to be recovered in summer (no LT effect). Cooling in summer can readily be achieved with most other LT systems.

Rating of emission systems

Enthalpy	**rating**	**notes**
floor heating	+++	Effect is about 1°C
wall heating	++	Smaller surface area and higher temperatures
enlarged radiators	+	Ditto
LT convectors	0	Neutral relative to HT systems
LT air heating	+	Options for cooling and heat recovery

3.4. Odour nuisance and other irritations

Proposition:

In LTH systems, the temperature of heating elements is mostly less than 10°C higher than the air temperature. In HT systems, this difference can be as high as 20 to 70°C. Dust scorch hardly occurs where heating elements have a low temperature. Dust scorch on hot elements renders dust more reactive and more ‘irritating’.

Supporting information:
Inhaled dust may initiate various allergic reactions. This is often the case when dust contains mite faeces, animal hair, fungi and fungal traces or pollen. Field tests have revealed a relationship between the degree of exposure to fine dust and worsening of asthma (asthma attacks), worsening of general complaints of the bronchial tubes (both upper and lower) and coughing. An effect on the lung function is also reported (lit [50]).

The extent to which buoyant dust and dust deposits cause health complaints depends on the dust composition (reactive and irritating components) rather than the concentration. A study by Mølhave (lit [74]) found that even low dust concentrations can trigger biological reactions in healthy persons. In that study, non-smokers were exposed to dust collected in offices that were known not to be ‘sick buildings’. The dust was

checked for cat and dog hair, mite faeces and other allergens. Only samples that were found to be free of these substances were used.
Inorganic (dust) particles may cause irritation, too, especially of the upper bronchial tract (nose and throat) and the eyes. Sammaljarvi (lit [75]) reports that the enlarged dust particles are retained in the upper bronchial tubes. These are highly sensitive in that they contain many nerve ends. Also, much immunologically active tissue is present here. Chronic irritation of the upper bronchial tubes produces excessive amounts of slime and attacks the cilia. Such irritation often is caused by exposure to irritating fibres, chemicals and scorched dust.
Sammaljarvi (lit [76]) advanced the hypothesis that at high heating temperatures the chemical composition of the air (dust) is more liable to cause diseases. He suspects that dust particles continuously burn on hot surfaces, an extreme example being electrical radiators whose outside surface can reach 90°C; the internal components can be as high as 300°C.
A supplementary investigation (lit [77]) corroborates Sammaljarvi's hypothesis. He identified the following factors that are conducive to building-related health complaints:
– high concentrations of volatile organic compounds;
– reactive finishing materials such as textile flooring materials;
– smoking;
– the presence of (visible) dust;
– heating elements with high surface temperatures.
In other literature (lit [78]), too, dust scorch on hot heating elements is reported to be a health hazard. In this case, the authors refer to a lower limit temperature of 50°C. In this way HT radiators, convectors and air heating have a disadvantage as normally components of these systems have surface temperatures exceeding this temperature limit. This explanations mostly deal with the effect of dusts scorch. It is expeded however that also air circulation plays a role in this (see also lit [78]).

Conclusion:

Wall and floor heating systems generate less airborne dust than HT systems, and the dust is less irritating, resulting in a lower incidence of eye and bronchial irritation and probably also of neurological complaints such as headache and fatigue.

Rating of emission systems

Odour and dust scorch	**rating**	**Notes**
floor heating	++	Lower temperature
wall heating	++	Ditto
enlarged radiators	+	Higher temperature and dust build-up
LT convectors	+	Ditto
LT air heating	+	Ditto

4. Energy consumption

4.1. Transmission losses

Proposition:

> Integrating heating systems in building elements causes a higher temperature of the building elements . The resultant transmission losses add to energy consumption. This is particularly relevant to floor heating on the lower floors and wall heating in exterior walls. Transmission losses from floors without improved insulation amount to about 1 m^3 gas/m^2 per year. For exterior walls this is 30 to 40% higher. Transmission losses can be reduced by reducing (turbulent) air flow along windows and the like. This does not apply to other LT systems.

Supporting information:
In most building regulations and/or standards on thermal insulation, requirements are given for partitions of heated occupied zones, regardless of whether the wall or floor contain any heating elements. In the Netherlands the minimum required Rc value for the building envelope is R_c = 2,5 m^2K/W.
The effect on transmission losses is calculated below for a surface area of one square metre.

	Starting points		**floor heating**		**HT radiators**	
-	$t_{heating}$ or T_i		25		18	°C
-	$T_{e,\ mean}$		5		5	°C
			20		13	°C
-	R_c construction	2.5		2.5	m^2.k/W	
-	u_e (from t_i to T_e)		0.388		0.362	w/m^2.K
-	heat flow to outdoors		7.75		4.71	W/m^2
-	additional heat loss for LT system		3.04		W/m^2	
-	burning hours for LT systems	3500		h/year		
-	surface area		1.0		m^2	
-	additional energy loss		10.6		kWh/year	
-	efficiency of heat supply		0.80		-	
-	gas combustion value		9.77		kwh/m^3	
-	weighting factor for floors (1/(U+1))		0.73		-	
-	additional fossil fuel loss for floors (nat.gas equivalents)		1.00		m^3/year	

The number of burning hours assumed here is relatively high in comparison with a traditional heating system. What is really meant here is the number of hours during which the system temperature in the floor averages 25°C. If the floor system is the primary heating system, a relatively low heat flow needs to be supplied during many hours. Accordingly, the number of burning hours is assumed to be 3,500. During the other hours transmission losses are assumed to be equal to those of a construction without LTH system. However, given the increasing use of energy conservation features, the heating season tends to become shorter, with fewer heating hours.

Gas consumption has been determined for a gas-fired boiler with a combined efficiency of 80% for heat generation and distribution. Heat losses due to the higher temperature of the building structure can be determined by dynamic calculations.
For a well-insulated structure they are about 5% of the heat input (lit [9], [14]). If the annual heat demand for space heating is 1,000 m^3 gas, the additional transmission losses are about 50 m^3 gas. This is in agreement with the above calculation for a floor area of 50 m^2. Lit [19] indicates that the additional losses are 0.54 m^3 gas/m^2 floor area for a floor of R_c = 3.0 m^2 .K/W and the same starting points.

LTH systems produce less (turbulent) air flow along the inside surface of exterior walls. Additional transmission losses are encountered here especially if the wall structure is poorly insulated. The higher air velocity affects convective heat transfer on the inside surface. This amounts to 30% of total heat transfer (convection plus radiation). Due to improved insulation, the α-value on the inside has a lesser effect on the heat lost to the outdoors. If R_c is 2.5 m^2.K/W, this is only about 5% (of which 1.5% convective). Normally, the effect of minor variations in the latter term on overall energy consumption is negligible. This is not the case for a hot radiator or convector beneath a large window with double-glazing . Convective heat transfer is significantly higher here (the U-value may be 40% higher), as is the temperature difference across the structure (due to the warm air flow on the inside). Olesen (lit [37]) reports that in poorly insulated structures these two effects cancel each other out. For HT systems the additional transmission losses are strongly dependent on local conditions. Lit [19] does not mention any higher or lower transmission losses for a Dutch reference dwelling, even though local temperatures and air velocities have been determined near the structural elements. Radiant heat transfer has been factored in also.

The additional transmission losses of floor and wall heating systems can be reduced by improved insulation of heated building elements. In this way they can even be reduced to zero in comparison with the reference system. The costs involved usually are only minor in comparison with the additional investment in the heating system (see also 5.3) but the energy savings that can be achieved with the emission system are significantly higher. Equivalent insulation is derived in 5.4.

Conclusion:

Transmission losses from exterior walls increase with increasing temperature and range from 0.5 to 1.5 m^3 gas per m^2 floor or exterior wall area with minimal insulation (moderate climates). Losses can be reduced or eliminated by locating heating elements, especially wall heating, in other building elements. Losses can also be reduced by applying thicker insulation. Transmission losses are lower for floor and wall heating due to lower air flows along exterior wall and windows. Losses also decrease with increased application of energy conservation measures, resulting in lower heat demand, and improved heat generation with higher efficiencies. All the same, it is
recommended that building elements containing heating elements should be better insulated than the minimum level according building regulations and standards.

Rating of emission systems

Transmission losses	**Rating**	**Notes**
floor heating	-	Losses to soil and crawl space; depending on insulation thickness and location
wall heating	-	Loss predominantly from exterior walls; depending on insulation thickness
enlarged radiators	0	Neutral relative to HT systems
LT convectors	0	If in pits, slightly better than HT systems
LT air heating	0	Neutral relative to HT systems

4.2. Ventilation losses

Proposition:

Ventilation losses are lower for floor and wall heating systems than for traditional systems. This adds to thermal comfort where LT radiators are used. No difference was found between LT convectors and air heating on the one hand the reference system on the other.

Supporting information:
As mentioned in 2.1, for equal thermal comfort in terms of the operative temperature, the required air temperature for LT floor and wall heating systems is lower than for traditional systems. At low air velocities, the operative temperature is the mean of radiant temperature and air temperature. Lit [12] cites the following equation for v_1 , 0.2 m/s:

$$\Theta_o = a * \Theta_1 + (1-a) * \Theta_{str.\ mean}$$

where
$a = 0.5$
Θ_o = operative temperature
Θ_1 = air temperature
$\Theta_{str.\ mean}$ = mean radiant temperature

Factor a is greater at higher air velocities, in which case more weight attaches to the air temperature.

Lit [14] includes a comparative evaluation of various heating systems for a person seated at the centre of a standard room. In each case the mean radiant temperature is calculated on the basis of the angle factors relating to the surrounding surfaces. Next, the air temperature needed to achieve the same thermal perception is calculated. Table 16 (lit [14]) shows the results for an outdoor temperature of +5°C. Olesen repeated the calculation for outdoor temperatures of –12°C and + of –12°C and +32°C. The values in Table 16 are most representative of an average (Dutch) heating season and thus may be used for energy calculations. The difference in air temperature between a floor heating system and a fully convective system is one degree Celsius at an operative temperature of 20°C.

Table 17: Effect on energy and gas consumption of lower air temperature (moderate climate)

Parameter	**Natural ventilation**	**Mechanical ventilation**	
$q_{v;n}$ infiltration	50.1	14.3	dm^3/s
$q_{v;m}$ mech. vent	-	33.0	dm^3/s
$q_{v;b}$ airing	23.0	23.0	dm^3/s
$q_{v;}$ total	73.1	70.3	dm^3/s
Spec. vent. heat loss	87.7	84.4	W/K
Vent heat loss/year	20863	20082	MJ
Vent heat loss[1]/year	19472	18743	MJ
δVent heat loss	1391	1339	MJ
η sys	0.95	0.95	(-)
η generation	0.90	0.90	(-) high efficiency boiler
δQprim heating	1627	1566	MJ
saving	46	44	M^3 gas/year

The energy performance can be determined using lit [80], which assumes that the mean temperature difference between indoor and outdoor air for moderate climates is 13°C. This results in a time-accumulated temperature difference of 238KMs.
Table 16 departs from a temperature difference of 15°C. If the difference were 13°C, the effect of floor heating in comparison with air heating would be 0.87°C, i.e. a difference of 12.1°C between indoor and outdoor air, resulting in a time-accumulated temperature difference of 222KMs. The difference in annual heat demand follows from Table 17, which is based on a standard air permeability $q_{v,10} = 1.43 * A_g$ and a heated area $A_g = 100\ m^2$ (corresponding will $n_{50} \approx 4$) (lit [80]). Calculations have been made for two ventilation systems and an (owner-operated) high-efficiency boiler. The temperature difference of 0.87°C is based on a fully convective system versus floor heating. An HT system using radiators (two elements with one or two convection profiles) operates mainly through convection. Lit [19] reports on detailed computer

simulations which reveal mean air temperature differences ranging from 1.8°C (for wall heating versus HT radiators) to 3.1°C (for floor heating versus HT radiators) while the system is operating. In this study the mean effect is estimated at one Kelvin, corresponding with potential energy savings of 1800 MJ.

For collective heating systems and those having a lower generation efficiency the energy savings can be higher than those stated in Table 17. Where balanced ventilation is applied the savings depend on the efficiency of the heat recovery unit. Failing heat recovery, the savings are equal to those relating to natural ventilation. With 65% efficiency, the potential saving is 33 m^3 gas per year.

Conclusion:

With LTH systems producing a high proportion of radiant heat, the occupants will tend to set the thermostat at a lower air temperature than for a traditional system to obtain an equal thermal comfort sensation. The difference in air temperature is about 1°C, equal to a saving a 40 to 50 m^3 gas for an average dwelling. No appreciable difference was found to exist between LT convectors and air heating and HT systems.

Rating of emission systems

Ventilation losses	**rating**	**notes**
floor heating	++	Lower temperature
wall heating	++	Ditto but to lesser extent
enlarged radiators	+	Ditto
LT convectors	o	Neutral relative to HT systems
LT air heating	o	Ditto, with heat recover options

4.3. Distribution and control losses

Proposition:

Heat losses occur as a result of heat transport and non-ideal temperature control. Distribution losses mainly occur in unheated areas and are dependent of the length, diameter and temperature of the pipework. Control losses depend on the location and positioning of the thermostat and the heat content of the system. Both types of heat loss are lower and better controllable if LTH systems are applied.

Supporting information:

Heat losses from pipework are by far the greater. Long pipe runs at relatively high temperatures are to be found especially in collective heating systems. This leads to energy losses and unwanted heat transfer (in for instance the wrong homes and places without actual heat demand). Such losses heavily depend on the system configuration and are substantially lower for LT systems. In the Dutch Energy Performance Standard (lit [90]), this loss is expressed in the system efficiency, i.e. the ratio of the amount of heat supplied to the system by the heat source to the effective amount of heat emitted by the system on an annual basis. The current issue of the standard cites a 5% loss for both individual and collective systems with individual metering. The loss is 15% for collective systems without individual metering. No distinction is made between LT and HT systems. In practice, losses of 10 to 15% may occur depending on the hydronic system lay outpipe, diameter changes and pipe insulation. In LT systems, the temperature difference between the medium and the air in an unheated space is about half as large as in a HT system. Thus, the losses will also be about half as large. This represents a saving of about 2.5% if the system is properly designed and about 5% for a poor design.

Control losses are heavily dependent on the control system used. This aspect deserves particular attention for LTH systems. Literature (e.g. Olesen) reports that good controllability can be achieved if the medium temperature is controlled by outdoor temperature and with a thermostat in each room, which should preferably respond to the operative temperature. LTH systems have an edge over their HTH counterparts in that they are (more or less) self-regulating. They have the drawback of the thermal mass of floors if structures are not insulated.

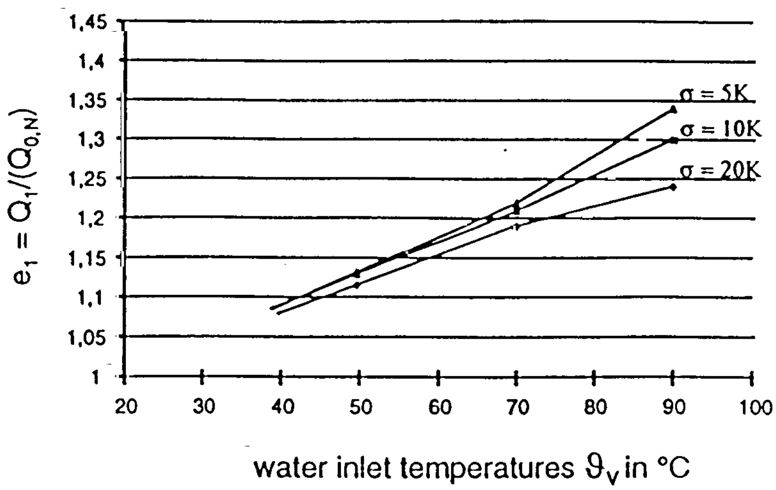
Lit [81] states the ratio of the supplied and required optimal amount of energy to the medium temperature (expenditure value e = 1). This is graphically represented in Figure 24. Bauer concludes that energy savings of 10 to 15% can be achieved by lowering the temperature.

There is not much point in night set-back in conjunction with wall and floor heating. If thermal mass is adequate and heat losses are low, its effect on temperature is only minor and causes discomfort in the morning because of low heating rates.

Conclusion:

Especially in collective heating systems, heat losses from pipework can be strongly reduced by opting for a LT system. Control losses can be reduced by proper temperature control in combination with the self-regulating properties of LTH systems. The effect of night set-back is only minor assuming a high level of insulation and relevant thermal mass. Because of these two factors, fuel savings range from 25 to 50 m^3 gas for an average dwelling.

Figure 24: Expenditure value at different supply temperatures



4.4. Transport energy

Proposition:

Transport energy is needed for conveying the heating medium. It is higher in LTH systems because of inherently higher flow rates and longer tube lengths. The difference is highest for floor and wall heating systems and is negligible for LT convectors and LT air heating. It can be reduced by proper sizing. There is less point in a pump on-off switch because of more uniform heat supply. Flow rate is about twice as high as in a HTH system. Additional electricity consumption is about 50 to 100 kWh per year.

Supporting information:
In low-temperature heating systems the difference between the supply and return temperatures is about half as large as in traditional systems (2.7). Thus, the medium needs to circulate at twice the flow rate for the same heat emission. On top of this, in wall and floor heating systems the tubing system is substantially longer than the pipework in a traditional system. Pump energy consumption is directly proportional to pressure loss, which in turn is directly proportionate to the tube length. Overall tube line length is dependent on the heat demand and tube spacing in the wall or floor, the latter typically being between 150 and 300 mm. Pressure loss (due to flow resistance) is inversely proportionate to the 5th power of the tube diameter. Thus, the larger tube length can readily be compensated for by selecting a slightly larger diameter. Lit [19] states that the energy consumption for a dia. 18 mm typically is 400 kWh. If the diameter is reduced to 14 mm, electricity consumption increases by 1,000 kWh per year. Pressure loss can also be reduced by installing parallel circuits.

Furthermore, it is important to develop a suitable control algorithm for the system. A less than optimum control strategy may require installation of two pumps. This can be prevented by selecting accurate three-way valves and protective devices. The control strategy for an LT system is simpler than for a HT system since careful temperature reduction on overheating is less likely to be needed.

Floor and wall heating systems, because of their thermal inertia, are less suitable for pump on/off switches. This applies especially to traditional systems with modulating pumps. A good control system should operate on the basis of the outdoor temperature with readjustment depending on the room temperature.

Electricity consumption of the pump in a traditional HT system in a single-family home is 175 to 200 kWh per year. A pump on/off switch can reduce this by about 100 kWh per year. Such switches are seldom, if ever, used in multifamily homes with a collective heating system. Instead, pumps are speed-controlled depending on the system pressure. In most cases the pumps are running continuously without the (collective) electricity consumption being metered.

The additional electricity consumption of LT systems such as wall and floor heating can thus be limited and depends on a good design and control system rather than the system parameters. Moreover, the heating season tends to become shorter as the level of insulation in new and renovated buildings improves. The application of LT systems often is an option in renovation projects where the heating capacity may become greater than demand because of additional energy conservation measures.

In the Netherlands excessive electricity consumption figures have been found for a number of projects with air heating systems. Such figures were not found for floor and wall heating systems in relation to the overall electricity consumption (lit [48]). Electricity consumption probably is 50 to 100 kWh higher for floor and wall heating because of the higher number of service hours and higher flow rates.

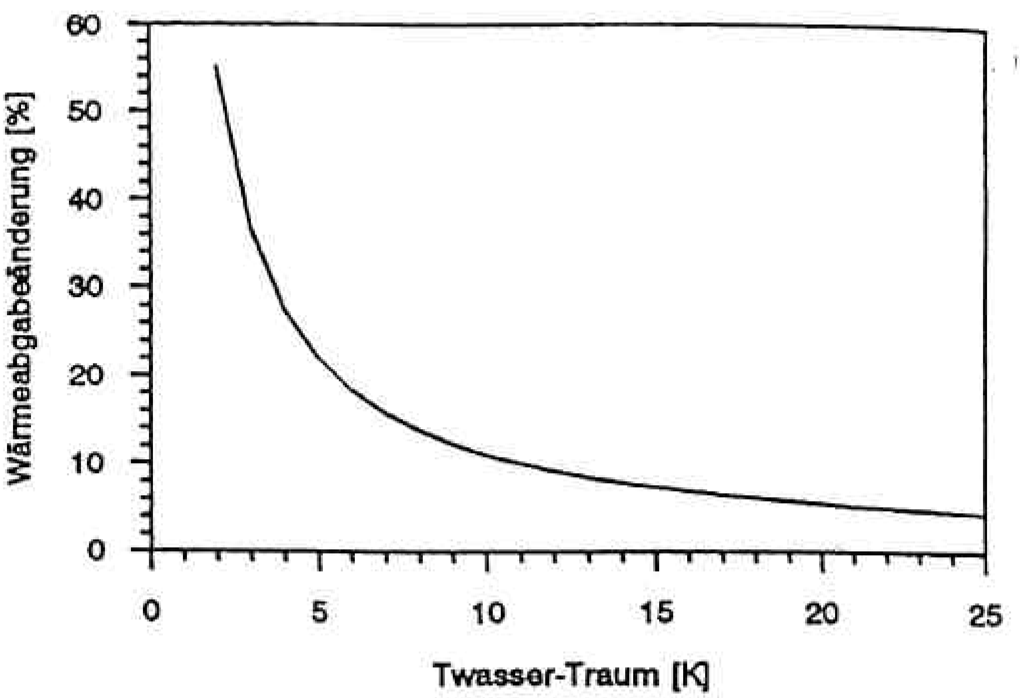
Conclusion:

Electricity consumption for transport energy is heavily dependent on the hydronic system layout, specially the tube length, diameter and the number of operating hours. This is particularly relevant to wall and floor heating systems. Pressure build-up because of the longer tube length can be prevented by selecting a larger diameter. The higher number of operating hours is inherent in the system and the higher flow rates needed for heat supply. It can be reduced by installing energy conservation features. Electricity consumption can be reduced by selecting a suitably large tubing diameter, by installing parallel circuits, proper control, modulating pumps and a low-energy building design.

Rating of emission systems

Transport energy	**rating**	**Notes**
floor heating	-	Additional pump energy depending on design
wall heating	-	Ditto
enlarged radiators	-	Ditto
LT convectors	0	Marginal effect
LT air heating	0	Ditto

Figure 25: Heat emission as function of temperature difference emission system and air temperature



4.5. Gains from solar radiation and indoor heat sources

Proposition:

The heat balance contains a number of gains and losses. Losses include transmission, ventilation and efficiency losses. Gains include gains from solar radiation and indoor heat sources. The balance eventually yields a particular heat demand. Heat gains cannot always be factored in, for instance incident solar radiation during periods of zero heat demand or when the required indoor temperature is exceeded. This is expressed in the heat gain utilisation factor. This factor is lower for well-insulated buildings than for poorly insulated buildings. LTH systems by their nature present a higher degree of utilisation than traditional systems.

Supporting information:
Heat entering a well-insulated building is largely absorbed by the thermal mass. The lower the energy losses, the longer such heat is retained within the building envelope. Where insulation is of a high level, the set-point temperature will be exceeded sooner, resulting in lower utilisation of solar and indoor heat gains. So long as the set-point temperature is exceeded, heat losses will be higher because of the higher indoor temperature. LT systems have a higher thermal mass than traditional systems and are also self-regulating. The first aspect plays a role only with light constructions. The second only if the heat not dissipated because of an indoor heat source can be utilised elsewhere in the circuit. This may be the case with a building in which the heat demand on the South side drops to zero because of the solar heat gain while a heat demand continues to exist on the North side. For both aspects it is essential that the system should be accurately controlled.

Fort (lit [32]) has investigated the dynamic properties of floor heating systems using TRNSYS (an advanced computer simulation model expanded to include floor heating systems). The study covered various LTH system designs (both wet and dry constructions), thermal mass (light, medium and heavy) and control systems (room thermostat, weather-piloted with and without measurement of incident solar radiation). The study does not include a comparison with HT systems. The calculations were validated by measurements in a PASSYS test cell. Figure 25 shows the self-regulating effect (lit [32]).
In the room with only a room thermostat, the circulation was interrupted by the air temperature rise brought about by the heat gains. Fort found that energy consumption increases by about 3 % (for light construction) when the solar and indoor heat gains cease to be redistributed in the building. Also, energy savings of 5 to 12% can be achieved by good, weather-dependent control in conjunction with a solar sensor.

Conclusion:

The gains from solar and indoor heat sources are difficult to quantify. Literature provides little information on this subject. The thermal mass of floor and wall heating system can make an appreciable difference especially where light constructions are used. Floor and wall heating systems offer better utilisation of heat gains by local cooling and heat redistribution in conjunction with their self-regulating effect. Potential savings probably are of the order of 1% for standard building designs.

Ratings of emission systems reviewed

Gains from solar radiation and indoor heat sources	**Rating**	**Notes**
floor heating	+	for light construction
wall heating	+	Ditto
enlarged radiators	0	probably negligible
LT convectors	0	Ditto
LT air heating	0	Ditto

Table 18: Energy use by year for different systems and sources (moderate climate)

Heating systems			**Source**	**Energy use**			
Temperature level	**Generic type**	**Specific type (1^{st} floor/2^{nd} floor)**		**[m^3]**	**[kWh]**	**[MJ]**	**[-]**
VLTS	0						
LTS	1	a	HEB	738	250	28206	0.94
	floor	(fl/fl)	HP1	0	2360	22355	0.74
	heating		HP2	0	2032	19251	0.64
		b	HEB	766	250	29179	0.97
		(fl/rad)	HP1	0	2438	23095	0.77
			HP2	0	2098	19875	0.66
		c	HEB	769	250	29287	0.97
		(fl+/rad/rad)	HP1	0	2446	23177	0.77
			HP2	0	2105	19944	0.66
	2	a	HEB	717	250	27450	0.91
	wall heating	(wall/wall)	HP1	0	2299	21779	0.72
			HP2	0	1981	18766	0.62
		b	HEB	744	250	28422	0.94
		(wall/rad)	HP1	0	2377	22519	0.75
			HP2	0	2047	19390	0.64
		c	HEB	758	250	28909	0.96
		(wall+rad/rad)	HP1	0	2416	22889	0.76
			HP2	0	2080	19701	0.65
	3		HEB	772	250	29395	0.98
	radiators		HP1	0	2455	23259	0.77
			HP2	0	2112	20013	0.66
MTS	5	b	HEB	787	250	29924	0.99
	floor	(fl/rad)	HP1	0	2745	26008	0.86
	heating		HP2	0	2311	21895	0.73
	7		HEB	794	250	30146	1.00
	radiators		HP1	0	2765	26196	0.87
			HP2	0	2327	22050	0.73
HTS	9		HEB	794	250	30146	1.00
	radiators						

HEB = High efficiency condensing boiler
HP = Heat pump

4.6. Effect of emission system on meter readings and registration of energy use

Proposition:

The effect of LT emission systems on energy consumption is not well understood yet. LT systems are more suited for renewable energy and are characterised by lower distribution losses. They result in a lower heat demand (due to lower ventilation losses, their self-regulating effect, etc.). Only little accurate information is available on the various factors that eventually determine energy consumption. Literature indicates that in any case the effect is not a negative one.

Supporting information:
The overall effect on energy consumption can only be determined by long-term evaluations lasting one to two years in dwellings with LT emission systems and identical dwellings in accordance with the reference. The number of dwellings should be large enough to be able to cancel out any particular heating habits of the occupants. Also, adjustments need to be made for climatic influences. A number of projects are currently under way in the Netherlands (Novem LTH-programme) but the results are not as yet available.

Lit [9] indicates that (referring to studies of Olesen and Kjerwlf-Jensen 1979) the energy consumption for floor heating is max. 10% lower than for other heating systems (based on nine system configurations). This study was conducted under laboratory conditions and in each case the same level of comfort was created with stationary conditions.

Olesen (lit [14]) found that for well-insulated homes the differences are only small. As pointed out in previous sections, the gain in respect of ventilation losses can be of the same order as the additional transmission losses in a poorly designed system.

Van Dijk et al. (lit [19] has calculated the overall energy consumption with reference to a HTH system with radiators and a high-efficiency boiler. He reports the following energy savings for a LTH system with a high-efficiency boiler:
- floor heating 6%;
- wall heating 9%;
- LT radiators 2%.

Further details are given in Table 18, along with the results for two heat pumps used for space heating. (HP1 (= heatpump 1) extracts heat from outside air and HP2 from the soil). This table is applicable for moderate climates.

Conclusion:

The meter readings depend on a set of diverse factors. The literature reviewed does not mention any adverse effect for LT floor heating. Savings accruing from the aforementioned effects probably are underestimated. No relevant effects have been found as to electricity consumption.

Figure 26: Temperature radiator surface depending on outdoor temperature (HT system)

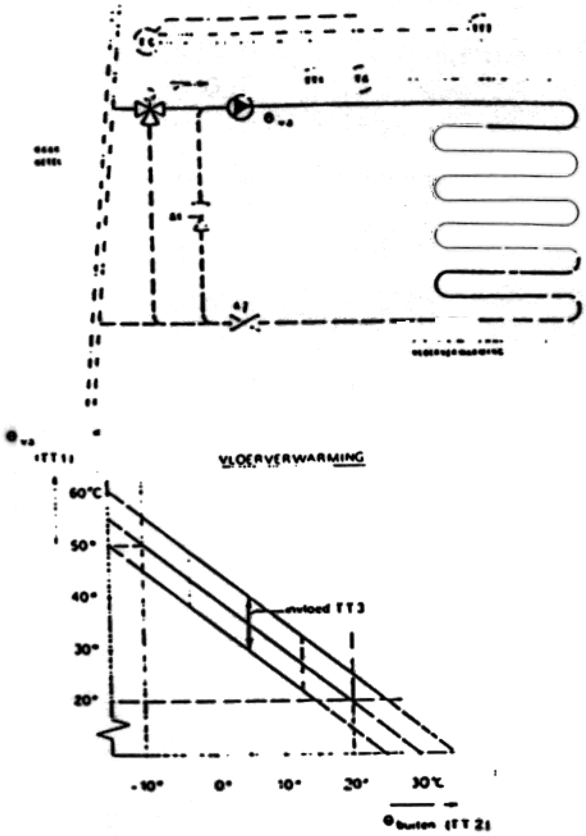
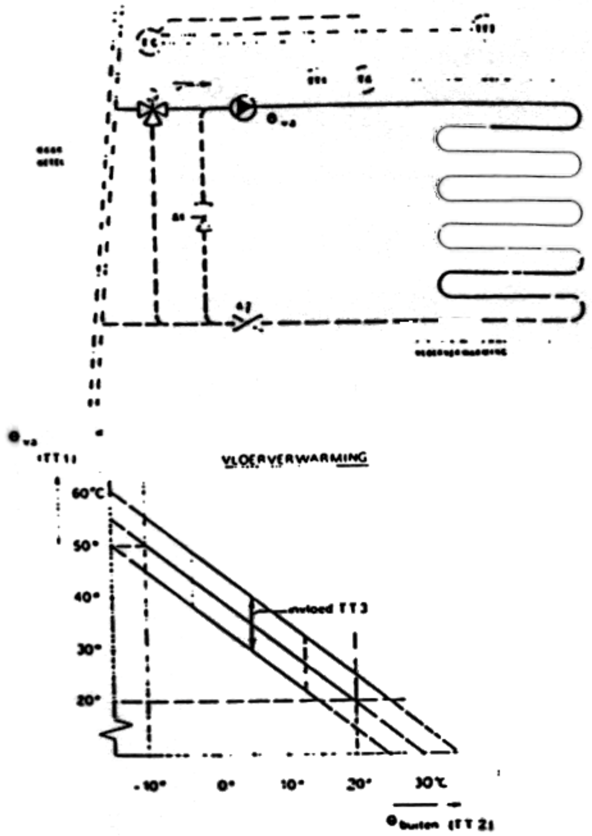


Figure 27: Temperature radiator surface depending on outdoor temperature (LT system)



5. Other aspects

5.1. Safety

Proposition:

Emission systems may pose two hazards: – skin burns – injuries The temperature of radiators may be as high as 90°C whereas LTH systems are max. 55°C. Skin burns may be sustained at temperatures higher than 40°C. Traditional systems often form an obstacle. As well as taking up an amount of space, they may cause injuries when someone falls onto them or hits them. Accordingly, radiators in homes for the elderly must meet additional requirements.

Supporting information:
A number of studies, including Lit [11] and [14], state that burns can occur at temperatures higher than 40 to 45°C. The surface temperature of radiators is virtually equal to the water supply temperature, which typically is 50 to 60°C at outdoor temperatures of about 0°C. At -10°C outside, the water supply temperature may increase to 90°C. This is also the case where heating-curve control is applied (Figure 26).

Figure 26 also shows that in the case of HT radiators with heating-curve control, the radiator temperature often exceeds the safe limit of 40°C when the outdoor temperature is below +10°C. The outdoor temperature often is below +10°C in the period from November to March. In this period there is a risk of burns on inadvertent contact with the radiators. This risk exists throughout the year where no heating-curve control (boiler on/off control) is used.

The heating curve of an LT radiator system is shown in Figure 27. The risk of burns is smaller here, but does exist. It does not exist with wall and floor heating. During the heating season, the surface temperature of a heated floor is between 20 and 30°C. Only seldom will it exceed 25°C where a high level of insulation is applied (lit [14]). In a well-insulated dwelling in which most of the walls are heated, the wall temperature will not exceed 30°C (lit [82]). If not all walls are heated, the temperature of heated walls may be somewhat higher but not higher than 35°C. Thus, there is no risk of skin burns on contact with wall and floor heating systems.

Conclusion:

LT heating systems such as wall and floor heating do not pose any risk of skin burns. HT radiators do pose such risk unless they are screened off. The risk of burns is only remote for HT air heating and convectors. As to the risk of injury, safe HT radiators are available at higher cost. Wall and floor heating systems do not involve any risk, nor does air heating. In the case of convectors and radiators, the risk depends on the design and construction.

Ratings of emission systems reviewed on safety

Safety	**Rating**	**Notes**
floor heating	++	Low temperature and no obstacles
wall heating	++	Ditto
enlarged radiators	+	Low temperature but extra obstacle
LT convectors	+	Depending on pipe routing and design
LT air heating	0	Neutral relative to HT system

5.2. Moisture in buildings

Proposition:

When a new building is drying out, the moisture is expelled more quickly by wall and floor heating. Also, more moisture is absorbed and desorbed from indoor air. Other LTH systems have no significant effect in this respect.

Supporting information:
Newly built buildings may contain high moisture concentrations due to the building techniques applied. Moisture is released to the indoor air for one to two years from completion. After this initial phase, the moisture balance in building structures is controlled by the following mechanisms:

- vapour diffusion due to differential vapour pressures;
- damp rising from the ground;
- moisture penetration;
- absorption and desorption.

Where wall or floor heating systems are used, unbound, liquid moisture which is present in buildings will evaporate more quickly due to higher temperatures of the building elements. Because of the higher temperatures, the risk of internal condensation will be lower. Absorption and desorption have a strongly regulating effect on the relative humidity of indoor air. This process mainly depends on differences in RH. The RH is low in heated buildings because of higher temperatures. When heating is switched off, the building elements absorb more moisture from the indoor air and do so at a higher rate. Such moisture is released again when the heating is switched on. Building elements probably exhibit a stronger regulating effect on a sudden increase in moisture content of the indoor air due to the occupants' activities. Lit [44] states that in a kitchen about 2 litres of moisture may be absorbed in the plastering. Little is known as to the effect of wall and floor heating systems in this respect. Their regulating effect probably is greater since hygroscopic and vapour equilibrium mechanisms tend to amplify each other.

Conclusion:

Wall and floor heating systems expel damp in new buildings more quickly than other heating systems. Once such damp is expelled, they probably also have a greater regulating effect on RH of the indoor air. Little information is available on the latter aspect.

Ratings of emission systems reviewed

Damp in buildings	**Rating**	**Notes**
floor heating	++	Greater hygroscopic effect and higher vapour transfer coefficient
wall heating	++	Ditto
enlarged radiators	0	Neutral relative to HT system
LT convectors	0	Ditto
LT air heating	0	Ditto

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