How a Building Heating Supply System Affects Energy Demand and Indoor Comfort

Carl-Eric Hagentoft, Ph.D. **Peter Roots, Ph.D.**

ABSTRACT

The heating supply system of a building affects both the energy demand and the indoor comfort. A debate regarding the efficiency of radiator and floor heating systems has been going on for awhile in Sweden. One side claims that the heat loss increases by 30% due to floor heating, and the other side claims that floor heating saves energy and that it improves the indoor thermal comfort.

In this paper, the heat loss and the thermal indoor comfort are simulated for both floor and radiator heating systems. The systems are evaluated as well or poorly insulated with thermally heavy and light buildings.

The simulation results show that the differences in indoor climate and operative temperature between the heating systems are small.

The floor heating systems have higher energy demand within the interval of 2% to 5% in the simulated examples. This is expressed by the performance factor (defined in the main body of the paper), which is less than one, which means that all the supplied heat is not transmitted to the interior. This factor depends on the foundation insulation resistance and the floor covering. The factor can easily be calculated from the U-factor of the floor and the thermal resistance between the pipe layer and the interior.

INTRODUCTION

Measurements in Sweden and Denmark of the total energy demand in single-family houses with floor heating indicate an increase of 30% to 40% in comparison with similar houses heated by radiators (Harrysson 1997; Radisch 2001). The conclusion is based on the measured total energy demand. On the other hand, the manufacturers of floor heating systems claim that floor heating systems save energy due to the fact that the indoor temperature can be reduced in comparison with a radiator heating system without degradation of the indoor thermal comfort. The argument for this is based on the fact that heat is transferred from the slab mainly by radiation (70%) and the rest by convection.

Olesen and Kjerulf-Jensen (1979) claim that floor heating saves energy and the heat loss is about 10% to 40% lower with floor heating compared with other heating supply systems. The conclusion is based on measurement in the stationary case in a room with only one external wall and with a foundation above a conditioned space (i.e., it is the same as a flat in an upper floor of a multi-family house, other then a ground-level floor). The floor heating is simulated with a heating foil on the floor surface. However, the results are not valid for embedded coils in concrete and certainly not for a single-family house. The floor covering (tile, wooden floor, carpets, etc.) represents a thermal resistance that will increase the heat loss. Roots (1998) shows that floor heating, in practice, will always result in a higher energy demand compared to radiator heating and that the difference depends on the floor covering. Hutchinson et al. (1950) and Sartain and Harris (1956) also report that floor heating results in higher heat losses, due to the thermal resistance of the floor covering.

The reported results are valid for buildings with low thermal capacity of the building envelope structures. In buildings with high thermal capacity, the control system has a major

Carl-Eric Hagentoft is a professor at Chalmers University, Göteborg, Sweden. **Peter Roots** is a researcher at the SP Swedish National Testing and Research Institute, Borås, Sweden.

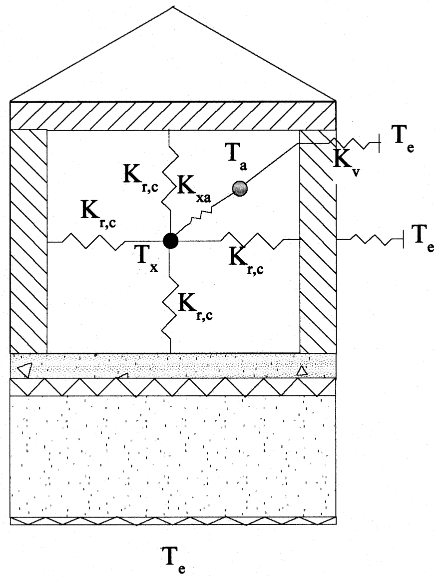

Figure 1 *The two-node simulation model. $K_{r,c}$ represents the thermal conductance due to radiation and convection between the surfaces and the room node with the temperature T_x. The thermal conductance, K_v, represents the coupling between the air node and the exterior air (i.e., ventilation). A soil layer of a thickness of 1 m is used below the floor structure in order to simulate the one-dimensional dynamic behavior of the ground thermal mass. Below the soil layer, a thermal resistance is added in order to get the correct overall U-factor from the interior to the exterior.*

influence on the heat losses in the transient case. In this paper, theoretical simulations are performed with the aim of comparing radiator and floor heating systems for the dynamic case. The model predictions will be compared with measured data in a follow-up project. The comfort criterion is based on the operative temperature of the room. The additional comfort that "warm feet" might give is not accounted for.

ENERGY DEMAND: RADIATOR VS. FLOOR HEATING SYSTEM

The heat losses in a building with floor heating can be determined using the global thermal performance factor, η (Roots 1998). It gives the fraction of heat that is supplied to the interior of the total released one. Using steady-state analysis, it can be calculated from

$$\eta = 1 - U_0 \cdot R_{in} \tag{1}$$

where R_{in} is the thermal resistance between the pipes and the interior air, and U_0 is the foundation U-factor, from interior to exterior air. Hagentoft (1991) shows that the local thermal performance factor can be simulated by applying boundary condition 1 as the interior temperature and 0 as the exterior one. The simulated steady-state temperature distribution at the position of the pipes gives the local thermal performance factor. This factor gives the relation between the heat transmitted to the interior to the total one from a single pipe. Using this remarkably simple rule, the local performance factor can be optimized.

The global thermal performance factor gives the relation between the overall transmitted heat to the interior to the totally supplied one. The factor is equal to one for the radiator heating system (i.e., all heat is released to the interior). With coils embedded in the concrete below the floor covering, the steady-state temperature, mentioned above, will be less than one, which results in a global performance factor less than one.

TABLE 1
Properties of the Building Envelope for Poorly or Well-Insulated Building Envelopes*

	Wall	Ceiling	Foundation	Window
U-factor (W/(m^2·K))	0.502/0.225	0.175/0.089	0.305/0.165	1.9/1.0
Insulation thickness (mm)	64/153	200/400	80/200	

* The thermal conductivity of the floor insulation is 0.04 W/m K and 0.036 W/m K for the other ones.

SIMULATION MODEL

The simulation is performed for a house with a single zone (room) (Figure 1). The type of building considered has a slab-on-grade (100 mm concrete) foundation. The water coils have a diameter of 15 mm and the distance between the pipes is 0.31 m. The air exchange rate due to the simple exhaust ventilation system is 0.5 1/h. The geometry of the building is 12-by-8-by-2.4 m. The location for the building is in Bromma near Stockholm in Sweden (average outdoor temperature equal to 4.3°C).

The simulations are performed for a building with heavy or light thermal capacity in the walls and the ceiling. Two cases of the thermal resistance of the building envelope are simulated—one poorly insulated (average U-factor 0.4 W/(m^2·K)) and one well insulated (average U-factor 0.2 W/(m^2·K)). The U-factor of the windows is 1.9 or 1.0 W/(m^2·K), with the area 15 m^2 facing south. The U-factor of the floor (foundation including soil) is 0.305 or 0.165 W/(m^2·K). The latter one represents new and very well insulated (cellular plastic) foundations that are used in combination with floor heating in Sweden. The properties of the building envelope are summarized in Table 1.

For the case of masonry buildings, the inner layer of the wall and the ceiling consists of 100 mm thick concrete. For low-mass buildings, a 13 mm gypsum board represents the interior layer. The outer layers consist of mineral wool. In both cases, the thermal resistance of the exterior cladding is accounted for.

The thermal network in Figure 1 is solved in a mathematical computing program. The model is built up using a building physics toolbox that is under development at our university. The computer program is an interactive tool for modeling, simulating, and analyzing dynamic systems. It enables you to build graphical block diagrams, using click-and-drag mouse operations, simulate dynamic systems, and evaluate system performance. Blocks for one-dimensional heat transfer components have been defined and developed for foundations and single- and multi-layer walls, based on finite difference schemes. Blocks for controlling heating and cooling, including floor heating, are also included.

The energy balance simulation for the ventilated building is based on a two-node model (Wit et al. 1987), using both the interior air temperature and an environmental temperature, T_x (Danter 1973). For the cases presented in this paper, the temperature T_x is a weighed average determined by the surface temperatures and areas (including radiatores), the air temperature, and the surface heat transfer coefficients due to radiation and convection. The radiative part of the internal gains also contributes to this temperature.

The two-node model assumes that

- the room air has a uniform temperature,
- all radiation (shortwave and emitted longwave) is distributed in such way that all surfaces absorb the same amount per unit of surface area, and
- the surface coefficients for convection and radiation are the same for all surfaces.

The assumption of uniform temperature is reasonable for the considered insulated and airtight buildings.

All interior thermal capacity is lumped into the air node. The floor heating system with the pipes is modeled for one representative cross section of the floor (Hagentoft 2001).

The operative temperature, T_{op}, is calculated by a weighing of the T_x temperature and the air temperature, T_a.

$$T_{op} = \frac{2 \cdot T_x + T_a}{3} \tag{2}$$

The floor and the radiator heating systems use a feed-forward control strategy. The steering is based on floating diurnal averages (24 h) of the external temperature. For the case with floor heating, the feed-forward temperature is calculated with following expression:

$$T_F = T_p + a \cdot (T_{dv} - T_e(t)) - b \cdot Q'_{gain}. \tag{3}$$

Here, Q'_{gain} represents a suitable, constant part of the internal heat gains; T_{dv}, the desired value of the operative temperature; and T_e, the exterior temperature. The temperature T_p is the average steady-state temperature at the position of the pipes for a building with an internal constant temperature equal to the desired one and no floor heating active.

The parameters a and b are given by

$$a = K_{tot} \cdot b \qquad b = \frac{1}{K} + \frac{1}{2 \cdot \eta \cdot Q_f \cdot \rho_f \cdot c_f}. \tag{4}$$

Here, K_{tot} (W/K) is the total conductance of the building (see Equation 7), and K (W/K) is the thermal conductance between the pipes in the concrete and the interior. The fluid flow in the circuit is Q_f (m^3/s), and the heat capacity of the fluid is $\rho_f c_f$ (J/m^3K).

The average water temperature, T_{av}, in the radiator (area, A, of 10 m^2 and heat transfer coefficient of $h = 7.7$ W/m^2K) is a function of the desired value that is equal to +22°C in the case studies. The average water temperature is controlled at

$$T_{av} = \frac{Q_{dv}}{A \cdot h} + T_{dv} \tag{5}$$

where

Q_{dv} = desired heat supply (W).

The heat loss is equal to

$$Q_{dv} = K_{tot} \cdot (T_{dv} - T_e(t)) - Q'_{gain} \tag{6}$$

$$K_{tot} = \rho_a \cdot c_a \cdot n \cdot V + \sum U \cdot A \tag{7}$$

Equation 7 represents the conductance for ventilation and transmission heat losses, where $\rho_a c_a$ is the volumetric heat capacity of air at constant pressure and n is the air exchange rate. U-factors and the corresponding areas of the building envelope are also used in order to get the total transmission heat losses. For the case study, the conductance K_{tot} is equal to 155.2 W/K for the poorly insulated building and 97.6 W/K for the well-insulated one.

Internal casual gains are simulated as periodic variations with the peak occurring between 18.00 and 6.00. The following data are used:

$$Q_{casual,\,gains}(t) = 500 + 500 \cdot \sin\left(2 \cdot \pi \cdot \frac{(t+6)}{24}\right). \tag{8}$$

Here, t, refers to the hour of the day with $t = 0$ representing midnight.

The annual average of the solar gains is 834 W, and the annual average external temperature is 4.33ºC. The annual average total internal gain (casual and solar) is 1334 W.

In the simulation, no additional ventilation or cooling is applied.

The performance factor presented from the simulations is based on the calculated annual average heat supply and internal gains.

$$\eta = \frac{Q_{loss} - Q_{gain}}{Q_{supply}} \tag{9}$$

For the radiator cases, the factor is equal to one.

TABLE 2
The Different Simulation Cases

Case	Mean U-factor of the building envelope	Ceiling, thermal capacity	Wall, thermal capacity	Heating system
1 (H/F)	0.4	Heavy	Heavy	Floor heating
2 (L/F)	0.4	Light	Light	Floor heating
3 (H/F)	0.2	Heavy	Heavy	Floor heating
4 (L/F)	0.2	Light	Light	Floor heating
5 (H/R)	0.4	Heavy	Heavy	Radiator
6 (L/R)	0.4	Light	Light	Radiator
7 (H/R)	0.2	Heavy	Heavy	Radiator
8 (L/R)	0.2	Light	Light	Radiator

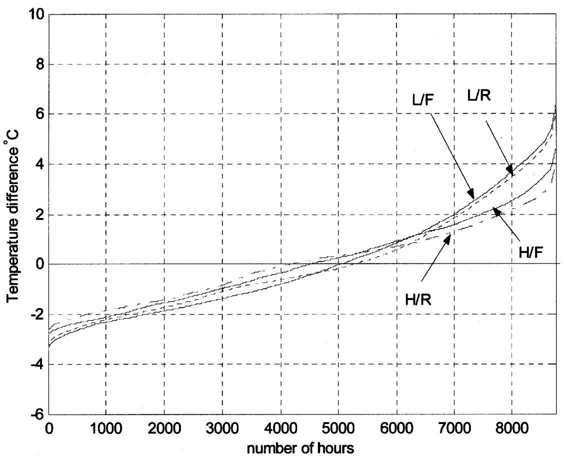

Figure 2 *Duration graph for the simulated operative indoor temperature for poorly insulated buildings. L/R stands for light building and radiator. H/F stands for heavy building and floor heating. The vertical axis represents the deviation in operative temperature from the annual average one. The horizontal axis represents how many hours per year a lower temperature difference, than the one read on the vertical axis, can be expected.*

CASE STUDIES

The simulations are performed for the cases when the thermal capacity is varying in the walls and ceiling. The mean U-factor of the building envelope (including windows) is either 0.2 or 0.4 W/(m^2·K). The simulations of the eight cases are summarized in Table 2.

The simulations have been performed for two years and the result from last year is presented.

RESULTS AND DISCUSSION

In Figures 2 and 3, duration graphs for the operative temperature for poorly and well insulated buildings are

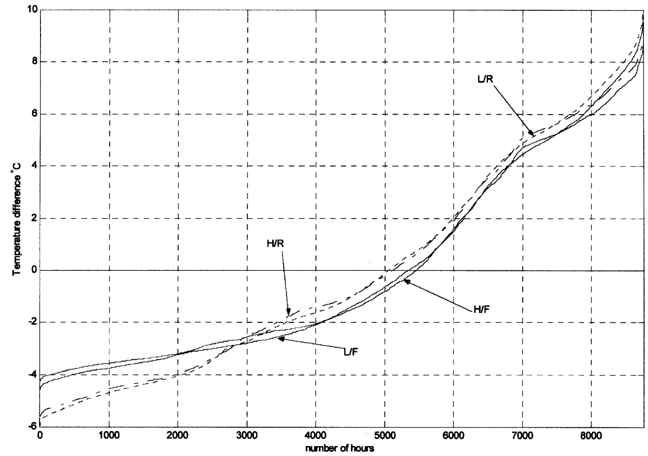

Figure 3 *Duration graph for the simulated operative indoor temperature for well-insulated buildings. L/R stands for light building and radiator. H/F stands for heavy building and floor heating. The vertical axis represents the deviation in operative temperature from the annual average one. The horizontal axis represents how many hours per year a lower temperature difference, than the one read on the vertical axis, can be expected.*

shown. The figures tell us that, for the poorly insulated building, the heavy structure offers the most stable indoor temperature, and the difference due to the heating system is minor. For the well-insulated building, the floor heating system offers a slightly more stable indoor temperature, and the thermal capacity of the structure is less important. The main differences, from the annual average temperature, occur during the hot period of the summer and the coldest period of winter. It is obvious that there is a need for cooling control during the summer, in particular for the well-insulated buildings. In reality, an increase in nighttime ventilation would reduce the degree of overheating. It is also clear that there should be a winter option for the heating control (i.e., a higher temperature of the water fed to the radiators and the floor is necessary). The control strategy in the simulations with the feed forward and radiator temperature according to Equations 3, 5, and 6 assume a constant internal heat gain, which obviously is not the case.

Figures 4 and 5 show the operative temperature for the poorly insulated building with floor heating for high and low mass. Figures 6 and 7 give the corresponding ones for radiator heating. These figures confirm the conclusion that the indoor temperature is more stable in the heavy buildings. The temperature in the poorly insulated radiator cases (both low and high mass) is obviously more comfortable during wintertime than for the corresponding floor heating cases. This is partially due to the bad control strategy for the midwinter period.

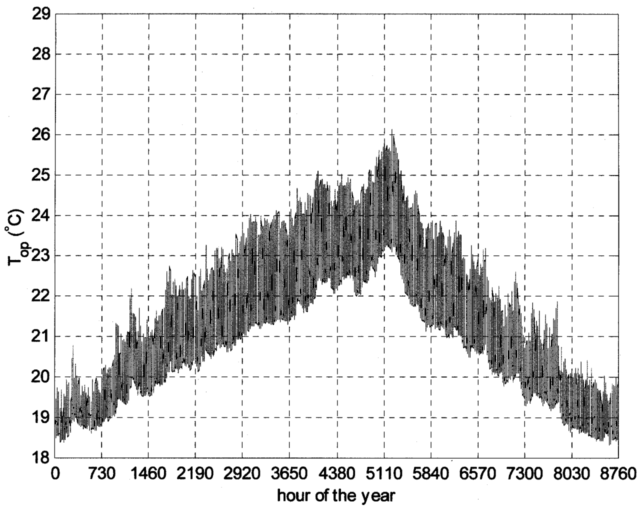

Figure 4 *Simulated operative temperature during one year for the case of a floor-heated poorly insulated heavy building, Case 1 (H/F).*

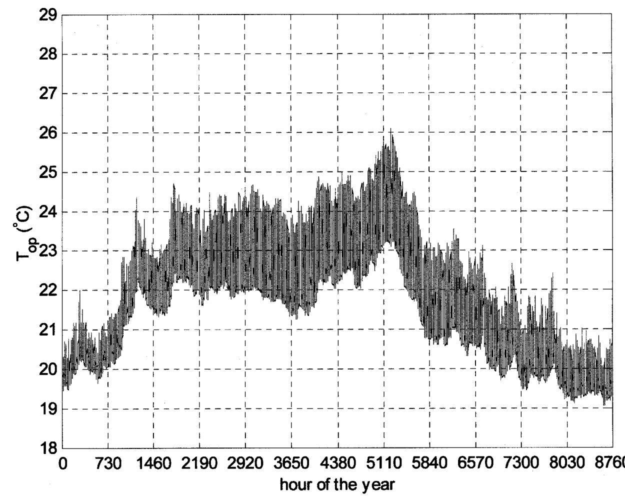

Figure 6 *Operative temperature during one year for a poorly insulated heavy building with radiator, Case 5 (H/R).*

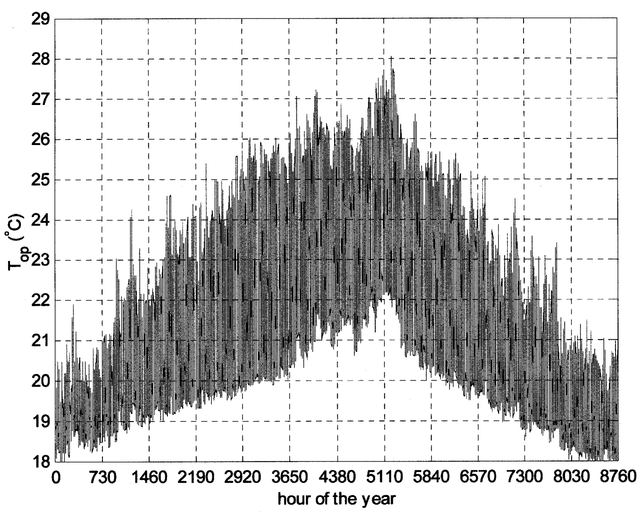

Figure 5 *Operative temperature during one year for the case of a floor-heated poorly insulated light building, Case 2 (L/F).*

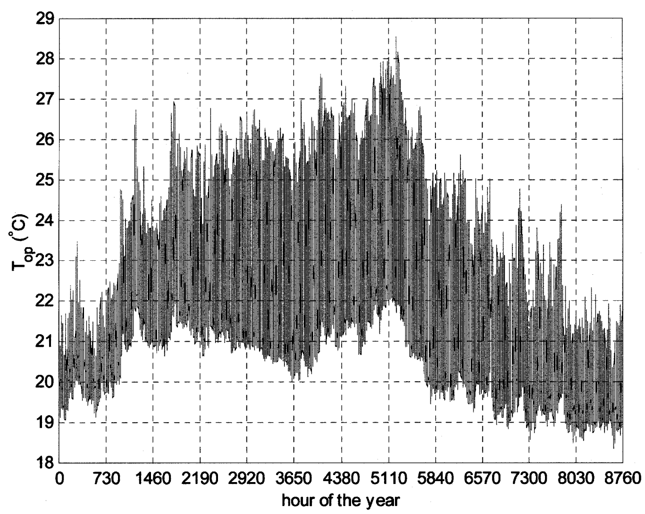

Figure 7 *Operative temperature during one year for a poorly insulated light building with radiator, Case 6 (L/R).*

TABLE 3
Annual Average Temperatures for the Simulated Cases

Case: U, heavy/light, heating system	T_a (°C)	T_{op} (°C)
0.4 heavy, floor heating	20.9	21.1
0.4 light, floor heating	21.0	21.2
0.2 heavy, floor heating	23.5	23.8
0.2 light, floor heating	23.6	23.9
0.4 heavy, radiator	21.5	21.7
0.4 light, radiator	21.5	21.7
0.2 heavy, radiator	23.1	23.4
0.2 light, radiator	23.2	23.5

TABLE 4
Yearly Heating Demand, Ey (kWh)—Difference between Floor and Radiator Heating*

Case: U, heavy/light, heating system	Ey (kWh)	Floor heating energy consumption vs. radiator (%)
0.4 heavy, floor heating	12 176	+ 5.5%
0.4 heavy, radiator	11 546	
0.4 light, floor heating	12 202	+ 5.3%
0.4 light, radiator	11 589	
0.2 heavy, floor heating	4 888	+ 2.4%
0.2 heavy, radiator	4 774	
0.2 light, floor heating	4 862	+ 3.2%
0.2 light, radiator	4 713	

* The numbers are corrected so that they correspond to the same annual average interior temperature.

TABLE 5
Yearly Heating Demand, Ey (kWh)—Difference Between Heavy and Light Buildings*

Case: U, heavy/light, heating system	Ey (kWh)	Floor heating energy consumption vs. radiator (%)
0.4 heavy, floor heating	12 176	~0%
0.4 light, floor heating	12 202	
0.4 heavy, radiator	11 546	~0%
0.4 light, radiator	11 589	
0.2 heavy, floor heating	4 888	~0%
0.2 light, floor heating	4 862	
0.2 heavy, radiator	4 774	~0%
0.2 light, radiator	4 713	

*The numbers are corrected so that they correspond to the same annual average interior temperature.

TABLE 6
The Global Thermal Performance Factor According to Steady-State and Dynamic Calculations

Case: U, heavy/light, heating system	Global thermal performance, Equation 9	Global thermal performance, Equation 1
0.4 heavy, floor heating	0.950	0.943
0.4 light, floor heating	0.950	0.943
0.2 heavy, floor heating	0.972	0.969
0.2 light, floor heating	0.974	0.969

Table 3 shows the annual average operative and air temperatures. The difference is less than 0.8°C, normally much smaller.

The energy demand for floor heating is higher than for radiator heating (see Table 4). The difference, however, is small. The largest difference occurs in the case of poorly insulated buildings. The results show that the energy demand is almost equal for light and heavy buildings (see Table 5) for these cases with heating only.

In Table 6, the global thermal performance factor, according to steady-state and dynamic calculations, calculated from the dynamic simulations, is compared with the ones calculated in Equation 1. The results tell us that there is only a small difference between them—less than 1%.

CONCLUSIONS

Radiator and floor heating systems have been theoretically simulated with the aim to analyze the difference in indoor temperatures and energy demand. The results show that the stability of the indoor temperature depends on the thermal capacity of the building for the poorly insulated building. However, for the well-insulated buildings, floor heating gives a slightly more stable indoor temperature. The energy demand is 2% to 6% greater for the floor heating system, depending on the floor insulation resistance. With floor heating, the foundation should be well insulated, at least on the order of what is used in the rest of the building envelope, in order to be energy efficient. For Swedish cases, a thermal resistance on the order of 4.2 m^2K/W or more can be recommended.

ACKNOWLEDGMENTS

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NOMENCLATURE

η	=	thermal global performance factor (-)
K	=	thermal conductance between the pipes in the concrete and the interior (W/K)
K_{tot}	=	total conductance of the building (see Equation 7), (W/K)
Q_f	=	fluid flow in the circuit (m^3/s)
Q'_{gain}	=	part of the internal heat gains (W)
$\rho_f \cdot c_f$	=	heat capacity of the fluid (J/m^3K)
R_{in}	=	thermal resistance between the pipes and the interior air
T_a	=	indoor air temperature (°C)
$T_e(t)$	=	external temperature (°C)
T_{dv}	=	desired temperature indoors (°C)
T_{op}	=	operative temperature (°C)
T_x	=	environmental temperature (°C)
U_0	=	foundation U-factor, from interior to exterior air

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