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Interaction of an air system with concrete core conditioning

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Abstract

In Europe, hydronic concrete core systems are being increasingly used for room conditioning systems. The concrete slab acts as heat accumulator and permits dissipation of the load using, for instance, cooling towers. When using such systems the external climatic conditions limit the achievable water temperature. The convective loads, however, directly affect the room air temperature and reduce the storable part of the load. The ventilation system also has a large influence on the energy related operation of such a system. Moreover, the dimensions of the concrete slab and the layout geometry of the water pipes, especially the spacing, are important factors for the design of the system. A model is described which can be used to illustrate the transient two dimensional heat flow in such a construction. This method is suitable for simple hand calculations, but can also be integrated into existing building simulation programs without having to modify the program code. Thus, the complete system can be designed for practical applications to ensure optimum operation. In addition, this paper describes the interrelationship between heat storage capacity and pipe geometry. Finally, criteria are listed for suitable application of concrete slab cooling and further aspects are listed that need to be considered in connection with these systems.

Keywords: Concrete core conditioning; Thermoactive core systems; Ventilation; Cooling; Modelling; Simulation; Design

1. Introduction

In Europe, water carrying systems are being increasingly used in room conditioning systems due to their high thermal efficiency. In contrast to panel cooling ceilings, in concrete slab cooling systems, plastic or steel pipes are encased in the concrete core. The concrete slab is therefore included in the heat transport mechanism and acts as heat accumulator which can be charged during periods when conditions for cooling are unfavourable and then, for instance, discharged during the night when outside temperatures are low. The concrete slab, however, can only store heat if its temperature can be continuously increased during the charging time. This causes a general increase in room temperature which is limited during the day due to comfort considerations for people present in the room. This criterion therefore limits the possible heat storage capacity of the concrete slab. Heat transfer from the heat source in the room to the surface of the concrete slab is by radiation and convection.

The major topics for the system planning engineer are the storable heat energy, the maximum output power plus the time and amount of the peak cooling power for the water system. The main design parameters are the water temperature, the space between the pipes and the operating times for heat discharge.

For the design of ventilation systems in combination with radiant cooling panels, several models have been developed [1]. With some limitations, also DOE-2 can be used [2] for this purpose. Model [3] can be used both for cooled ceilings as well as concrete core cooling systems.

For the design of concrete core cooling and heating systems, in the following named thermoactive core systems (TACS), the temperature distribution in the slab has to be considered in more detail. Finite Element (FE) or Finite Difference (FD) codes can produce such distributions as long as the boundary conditions are known. Unfortunately this is not the case in TACS design, because of the interaction between the slab under consideration with the room air, the adjacent surfaces and the heat sources.

Therefore, the FE or FD model has to be integrated into the thermal room or building model. This has been done in Ref. [3] and earlier by Fort, originally, for floor heating system design [4], but later also for the design of TACS,

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such as the one in the 'Dow' building where performance evaluations have also been made [5].

Nevertheless, FE or FD models require mostly large input and also lead to significant increases in computation time. Therefore, a simpler approach has been developed. This paper gives a model for the description of the transient temperature distribution in the slab, which is practical for both hand calculations and integration into a building simulation code, and outlines the design procedure for TACS.

2. Procedure for determining dimensions of core slab and pipe spacing

2.1. Convective heat balance of room

The convective heat balance of the room is obtained from (for parameters, see Section 7):

$$\sum_{j=1}^{n} h_{c_j} \cdot (T_a - T_{s_j}) \cdot A_j = \dot{Q}_c - \dot{m} \cdot c \cdot (T_a - T_{su}). \qquad (1)$$

From Eq. (1) it can be seen that the less the convective heat load $\dot{Q}_c$ is directly removed by the air system temperature difference, the higher is the difference between the room air T_a and the outer surface T_s. As the convective heat transfer coefficient h_c is in the range 1.5 to 2.5 W/m^2 K, even a relatively small convective heat flow into the slab surface already causes a considerable temperature difference between the air and the surface.

If a heat source is switched on at the start of the working day, within a very short time it releases its convective portion into the room air. The air temperature at the starting point (1) in Fig. 1 increases rapidly to a certain value (point (2)), while the surfaces can take up the radiated portion of the source without a large increase in temperature due to their storage capacity. The same response of the room air temperature, this time in the other direction (from point (3) to (4)) can be observed at the end of the working day when the heat source is switched off. The maximum allowable increase of the room air temperature $\Delta T_{a,max}$ during the day (from point (1) to (3)) is limited by comfort criteria. From the author's experience, 3 to 4 K for $\Delta T_{a,max}$ are widely accepted values among HVAC designers.

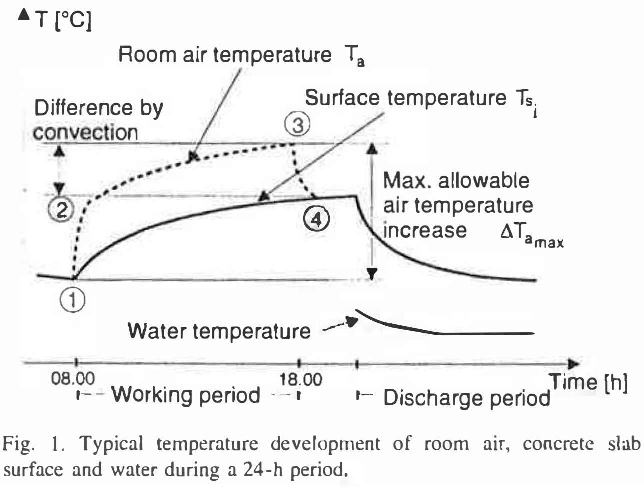

Fig. 1. Typical temperature development of room air, concrete slab surface and water during a 24-h period.

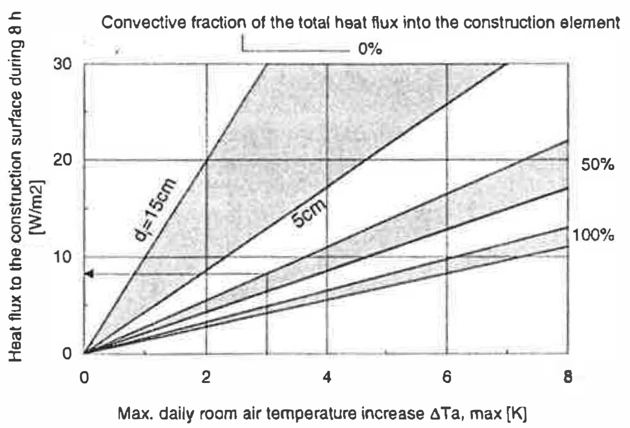

Fig. 2. Estimate of the heat flow absorbed per slab surface for a concrete construction of 10–30 cm thickness ($d_1 + d_2$ in Fig. 3) with a heat source 8 h in operation and no cooling during this period. (Example: for $\Delta T_{a,max} = 3$ K and a 50% convective heat source, a slab surface with water pipes at 15 cm depth absorbs a heat flux of approximately 8 W/m^2).

The greater the convective temperature jump (point (1) to (2)), the smaller the possible temperature increase of the concrete slab and therefore its storage capacity. In order to minimize the convective temperature jump, it would be necessary to remove the entire convective heat load via the ventilation system. It would be even better to ensure that the convective heat cannot dissipate into the room, by carrying out suitable measures, like, e.g., direct extraction at the heat source. If the ventilation system has to extract a large heat load, either a large air flow or a large temperature difference between the room air and the supply air must be available. Because the air supply system contributes significantly to the total energy consumption of the system, the air flow rate is usually reduced to the minimum given by the air quality requirements. If the cooling of the room is to be carried out using direct cooling methods, the achievable temperature difference between the supply air and the room air is limited and therefore also the convective heat removal capacity of the ventilation system.

2.2. Storable energy in the concrete slab

An initial estimate for a concrete construction with a thickness of 10–30 cm (Fig. 2) illustrates the strong impact of the convective portion of the load on the achievable heat flow in the concrete slab (for a given maximum allowable room air temperature increase $\Delta T_{a,max}$ during the day).

Further investigations are needed to show to what extent it is useful in terms of energy aspects to increase the air volume rate and thus, reduce the convective heat flow into the concrete slab.

2.3. Determining the water temperature

The water temperature required to cool the heat-charged concrete slab back to the initial level within a day (load cycle), is of great interest. This temperature depends on the material properties, the diameter and the spacing of the water pipes, and the vertical position of the pipe level in the concrete slab.

A temperature profile is set up between two water pipes in the concrete which creates a two-dimensional temperature distribution (see Figs. 3 and 4). The form of this profile depends to a great extent on the momentary heat flow into the pipes. The achievable stationary heat flow at one side of the concrete is described by the following equation:

$$\dot{q}_1 = \Phi \cdot U_1 \cdot (T_w - T_{a_1}) + (1-\Phi) \cdot \frac{U_1 \cdot U_2}{U_1 + U_2} \cdot (T_{a_2} - T_{a_1}). \qquad (2)$$

Φ is the form factor, taking into account the characteristics of the pipe in the slab. Values for Φ can be calculated for various layouts by using the shape factor theory [6,7]. U_1 is the heat transfer coefficient through the slab from the pipe level to the room air. The first term on the right hand side of Eq. (2) describes the heat flux produced by the difference between the temperature of the water and the room air. In this case, the heat transfer coefficient U_1 is corrected by the form factor in order to compensate for the two-dimensional temperature distribution. The second term in Eq. (2) describes the heat flow progressing from one side of the room to the other through the slab. With no pipes in the slab, the form factor $\Phi = 0$ and we obtain from the equation precisely the heat transfer through a slab layer of the thickness $d_1 + d_2$.

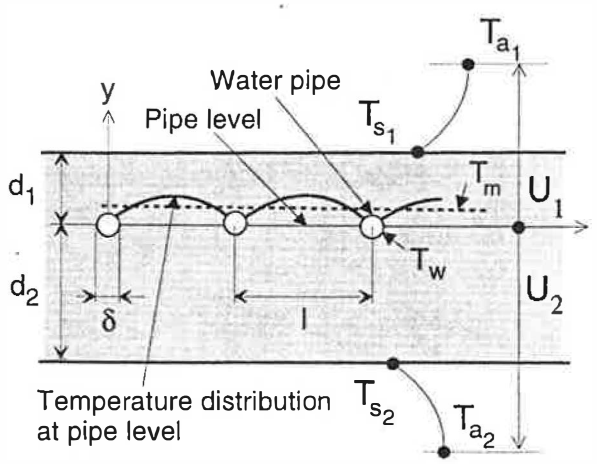

Fig. 3. Schematic drawing of the geometry and the temperature parameters for concrete slab cooling, including a sketch of the temperature distribution in the plane of the water pipes.

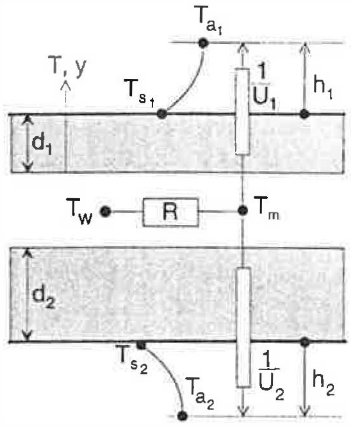

Fig. 4. One-dimensional model for the calculation of the heat transfer through the concrete slab.

The total heat flux from the water pipes to both sides of the concrete slab is determined by the following equation:

$$\dot{q} = \dot{q}_1 + \dot{q}_2 = \Phi \cdot \left[U_1 \cdot (T_w - T_{a_1}) + U_2 \cdot (T_w - T_{a_2})\right]. \qquad (3)$$

It can be shown [8] that the same result as in Eq. (3) is achieved if a mean temperature at the pipe level between the pipes is defined and then calculated according to the laws of one-dimensional thermal conduction:

$$\dot{q} = \dot{q}_1 + \dot{q}_2 = U_1 \cdot (T_m - T_{a_1}) + U_2 \cdot (T_m - T_{a_2}). \qquad (4)$$

If Eq. (3) is equated with Eq. (4) and resolved for this mean temperature at the pipe level, we obtain:

$$T_m = \Phi \cdot T_w + (1-\Phi) \cdot \left[\frac{U_1}{U_1 + U_2} \cdot T_{a_1} + \frac{U_2}{U_1 + U_2} \cdot T_{a_2}\right] \qquad (5)$$

or Eq. (4) put into Eq. (5) again and transformed according to $\dot{q}$:

$$\dot{q} = \left(\frac{\Phi}{1-\Phi}\right) \cdot (U_1 + U_2) \cdot (T_w - T_m). \qquad (6)$$

By putting the calculation formula for Φ [9] into Eq. (6), we obtain:

$$\dot{q} = \frac{2 \cdot \pi \cdot \lambda}{l \cdot \left[\ln\left(\frac{l}{\pi \cdot \delta}\right) + \sum_{s=1}^{\infty} \frac{g_1(s) + g_2(s)}{s}\right]} \cdot (T_w - T_m). \qquad (7)$$

with:

$$g_i(s) = \frac{\dfrac{\frac{h_i}{\lambda}\cdot l + 2\cdot\pi\cdot s}{\frac{h_i}{\lambda}\cdot l - 2\cdot\pi\cdot s}\cdot e^{-\frac{4\cdot\pi\cdot s}{l}\cdot d_{3-i}} - e^{-\frac{4\cdot\pi\cdot s}{l}\cdot(d_1+d_2)}}{e^{-\frac{4\cdot\pi\cdot s}{l}\cdot(d_1+d_2)} - \dfrac{\frac{h_1}{\lambda}\cdot l + 2\cdot\pi\cdot s}{\frac{h_1}{\lambda}\cdot l - 2\cdot\pi\cdot s}\cdot\dfrac{\frac{h_2}{\lambda}\cdot l + 2\cdot\pi\cdot s}{\frac{h_2}{\lambda}\cdot l - 2\cdot\pi\cdot s}} \quad (8)$$

The first term on the right hand side of the equals sign in Eq. (7) can be interpreted as a heat transfer coefficient between the water temperature and the mean temperature at the pipe level in the slab. The sum term in Eq. (7) describes the boundary value adjustment. It can be shown [10] that this term can be ignored for practical applications with a ratio $d_i/l > 0.3$ and $\delta/l < 0.2$.

The heat transfer through the concrete slab (Fig. 3) can also be approximated by the one-dimensional heat transfer through two slab plate layers and an additional resistance R on the water side. This is shown schematically in Fig. 4.

Fig. 5 shows the values of the additional heat transfer coefficient $1/R$ for pipes in a concrete construction as a function of the diameter of the pipes and the gap between them (steel pipes).

In transient cases, the resistance term in Eq. (7) actually is time-dependent, but steady state conditions are reached within reasonable time constants compared to the normally used 1 h time step for the simulation [11]. Therefore, the procedure outlined is applicable for both steady state and transient calculations. In addition, it can be easily integrated into thermal simulation programs. This is outlined in more detail in paragraph 4.

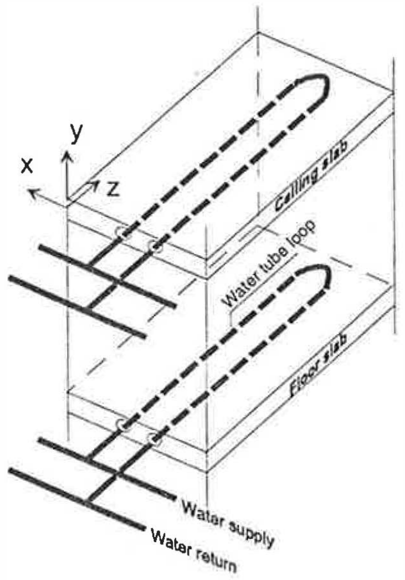

Fig. 6. Typical arrangement of slab cooling pipe loops.

In order to calculate the necessary water temperature for a given construction and load profile, the transient heat transfer must be calculated through both sides of the concrete slab. As in most simulation programs, both analytic solutions [12] and numerical methods [13] are used for this calculation. The required water temperature can then be calculated from this result using Eq. (7). If the heat flow into the water is kept constant, for instance by discharging during the night, the difference between the water temperature and the mean temperature in the water pipe level can be calculated directly from the dissipated power and the heat transfer coefficient according to Fig. 5.

3. The third dimension

In the individual pipes, the water temperature rises from the supply to the return temperature level according to the

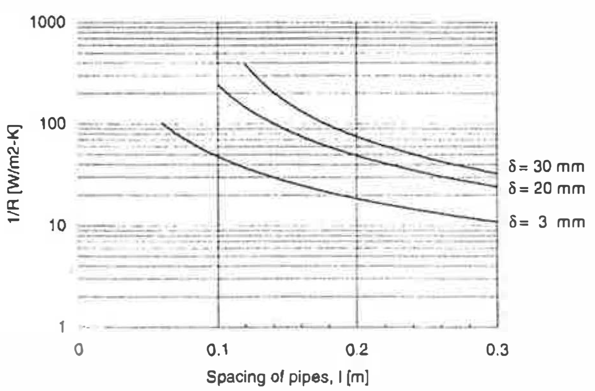

Fig. 5. Heat transfer coefficient for a concrete construction on the water side as a function of the pipe diameter and spacing ($d_i/l > 0.3$).

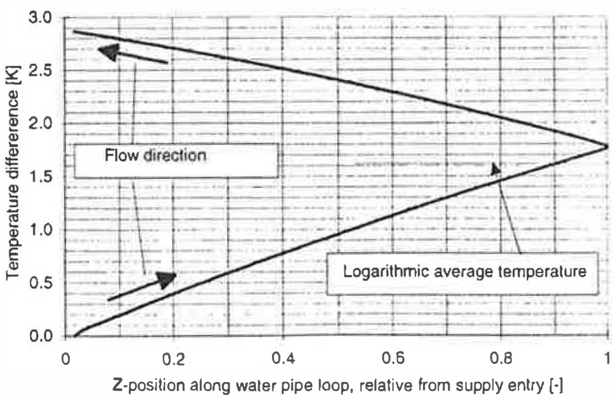

Fig. 7. Typical water temperature distribution along a slab cooling pipe loop (in z-direction, see Fig. 6).

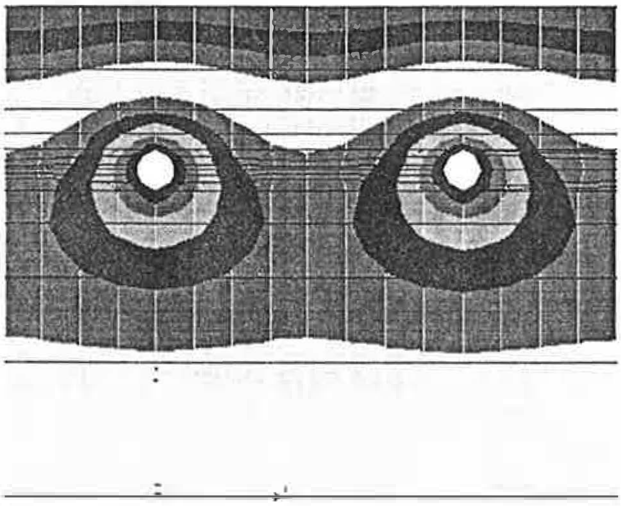

Fig. 8. Temperature distribution in the slab for load conditions as in Fig. 9 (at 7 p.m.), transient FE calculation.

load. This has to be considered when reducing the case to a two- and, further, to a one-dimensional problem.

In many cases, the individual water pipes are connected in a loop, the main supply and return ducts being on the same side of the slab, as outlined in Fig. 6.

A typical water temperature distribution for such a case is given in Fig. 7. For such arrangements of the pipes, one value for the average temperature T_w must be determined from the water temperature distribution in the loop. An approximation can be made by using the logarithmic average on the basis of the room air temperature. Another possibility is to partition the slab in the z-direction.

4. Validation of the model

Validations of the model have been performed by comparison against results from both analytical and FE (Finite Element) calculations.

In the two-dimensional case presented here, the pipes are asymmetrically placed in the slab (pipe diameter 25

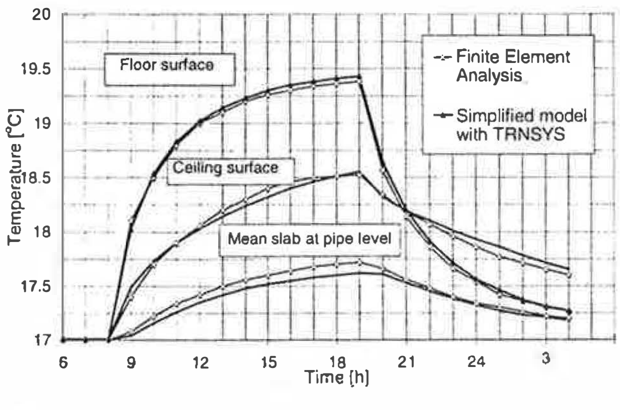

Fig. 9. Temperatures at both floor and ceiling surfaces and at the water pipe level in the slab (T_m) for both calculation methods.

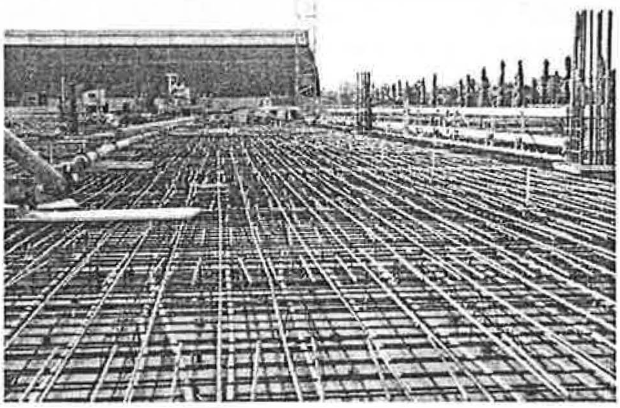

Fig. 10. Floor slab of the new Zurich fair exhibition hall just before concrete pouring. Water pipes extent between the steel reinforcements.

mm, spacing 200 mm, $d_1 = 100$ mm, $d_2 = 200$ mm, see also Fig. 8). The water temperature is constant at 17°C. With initial conditions at 17°C, a room air step function is applied at 8 a.m. from 17°C to 20°C (lower room) and from 17°C to 25°C (upper room). After 7 p.m., the heat flux at the surfaces is reduced to zero.

In this case, the concrete slab model is used in combination with the building and system simulation program TRNSYS [14], specifically with its multizone building model. The slabs with the water pipes are modelled as two 'walls', separated by a dummy zone representing the water system, with heat transfer coefficients according to the resistance R (see Figs. 4 and 5).

Results of these simulations were also compared with transient FE analysis. In general, quite good agreement was observed (see Fig. 9).

5. Application

The model has been used so far for the design of the TACS of the new exhibition hall of the Zurich fair, which is presently under construction (Fig. 10).

6. Conclusions

6.1. Specifications and recommendations for concrete slab cooling

Specifications for the application of concrete slab cooling and recommendations for practical use are as follows: (1) Heat transfer to the concrete slab must not be jeopardized by carpets or dropped ceilings. (2) An increase of the room air temperature, within the comfort range, during the occupation time of the room must be allowed. (3) With a higher radiative portion of the heat load, the heat storage capacity of the concrete slab is better utilized. (4) A

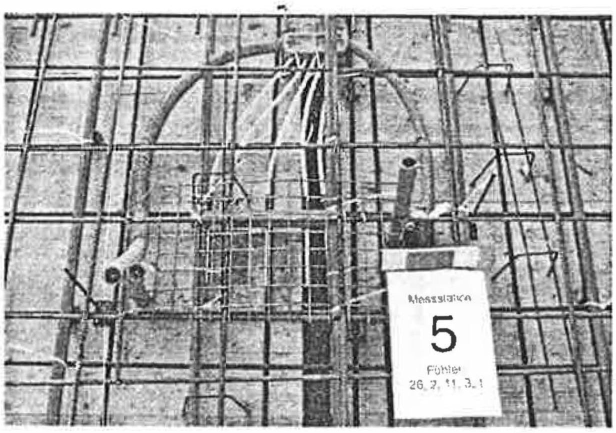

Fig. 11. Temperature sensors are installed in the slab along a water pipe loop.

ventilation system must be available which can remove parts of the convective heat load. The load split between ventilation and concrete cooling system must be determined in each individual case. In most cases, the required ventilation rates will be larger than the minimum values according to air quality requirements. (5) The water network in the concrete can be used for cooling and heating purposes.

6.2. Future research needs

The following points need to be studied and investigated more closely in any future work:

- Increased generalization of the model, in particular for the inclusion of the third dimension (spatial temperature distribution along the water loop)
- Design of the complete system taking into consideration refrigeration (for air and water system), the ventilation system and operational aspects
- Control, operation: Criteria and information for optimizing the operation of the complete system
- Heat storage capacity of various room types
- Application ranges and application limits for thermoactive building components
- Comparison to pure air system solutions both in terms of investment and operational cost
- Measurements in real buildings.

Most of this topics are treated in a project which has recently started at EMPA. This project also includes measurements in the already mentioned new exhibition hall of the Zurich fair (see Fig. 11) and simulation work for the optimization of such systems in general, as well as, in particular for this case.

7. Symbols and units

A	surface (m^2)
c	specific heat capacity (J/kg K)
d	insertion depth (m)
h	heat transfer (W/m^2 K)
l	gap between pipes (m)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat flow (W)
$\dot{q}$	specific heat flow rate (W/m^2)
R	resistance (m^2 K/W)
T	temperature (°C)
t	time (s)
U	overall heat transfer coefficient (W/m^2 K)
δ	pipe diameter (m)
λ	thermal conductivity (W/m K)
Φ	form factor

Indices

1	zone 1
2	zone 2
i	zone i
j	wall number
a	air
c	convective
m	average
s	surface
su	supply air
w	water

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Andreas Weber and Robert Weber contributed with simulation work and Peter W. Egolf with many helpful suggestions. This work has been financially supported by the EMPA, the NEFF (Swiss National Energy Research Fund, project 640) and the Swiss Federal Office of Energy (BEW, project erg).

References

[1] M. Koschenz, Simulation of displacement ventilation and radiative cooling, Proceedings 14th AIVC Conference, Denmark, 1993.
[2] G. Zweifel, M. Koschenz, Simulation of displacement ventilation and radiative cooling with DOE-2, ASHRAE Meeting, Denver, 1993.
[3] C. Stetiu, H.E. Feustel, F. Winkelmann, Development of a simulation tool to evaluate the performance of radiant cooling ceilings, LBNL-37300, 1995.
[4] K. Fort, Dynamisches Verhalten von Fussbodenheizungen, PhD Thesis No. 8893, Swiss Federal Institute of Technology, ETHZ, 1989.
[5] R. Meierhans, Untersuchungen an einem Bürogebäude mit passiver Nachtkühlung der Betondecke, Project report NEFF, Swiss National Energy Research Fund, 19961, p. 464.
[6] Ö.M. Neati, Heat Transfer, McGraw-Hill, New York, 1985.
[7] VDI-Wärmeatlas, Berechnungsblätter für den Wärmeübergang, VDI-Verlag, Düsseldorf, 1991.
[8] B. Glück, Strahlungsheizung, Verlag C.F. Müller, Karlsruhe, 1982.

[9] B. Glück, Wärmeübergang, VEB Verlag für Bauwesen, Berlin, 1989.
[10] M. Koschenz, V. Dorer, Design of air systems with concrete slab cooling, Proceedings ROOMVENT '96, Japan, 1996.
[11] M. Koschenz, A model for concrete slab cooling, EMPA Internal Report 175-IB9603mk, 1996.
[12] H.S. Carlsaw, J.C. Jaeger, Conduction of Heat in Solids, Oxford Univ. Press, 1959.
[13] G.P. Mitalas, Calculation of transient heat flow through walls and roofs, ASHRAE Annual Meeting, New York, 1968.
[14] TRNSYS, A Transient System Simulation Program, University of Wisconsin, Madison, 1994.