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Building environment design — Design, dimensioning, installation and control of embedded radiant heating and cooling systems —

Part 4: Dimensioning and calculation of the dynamic heating and cooling capacity of Thermo Active Building Systems (TABS)

Conception de l'environnement des bâtiments — Conception, construction et fonctionnement des systèmes de chauffage et de refroidissement par rayonnement —

Partie 4: Dimensionnement et calculs relatifs au chauffage adiabatique et à la puissance frigorifique pour systèmes thermoactifs (TABS)

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 11855-4 was prepared by Technical Committee ISO/TC 205, *Building environment design*.

ISO 11855 consists of the following parts, under the general title *Building environment design — Design, dimensioning, installation and control of embedded radiant heating and cooling systems*:

— Part 1: *Definition, symbols, and comfort criteria*

— Part 2: *Determination of the design and heating and cooling capacity*

— Part 3: *Design and dimensioning*

— Part 4: *Dimensioning and calculation of the dynamic heating and cooling capacity of Thermo Active Building Systems (TABS)*

— Part 5: *Installation*

— Part 6: *Control*

Part 1 specifies the comfort criteria which should be considered in designing embedded radiant heating and cooling systems, since the main objective of the radiant heating and cooling system is to satisfy thermal comfort of the occupants. Part 2 provides steady-state calculation methods for determination of the heating and cooling capacity. Part 3 specifies design and dimensioning methods of radiant heating and cooling systems to ensure the heating and cooling capacity. Part 4 provides a dimensioning and calculation method to design Thermo Active Building Systems (TABS) for energy-saving purposes, since radiant heating and cooling systems can reduce energy consumption and heat source size by using renewable energy. Part 5 addresses the installation process for the system to operate as intended. Part 6 shows a proper control method of the radiant heating and cooling systems to ensure the maximum performance which was intended in the design stage when the system is actually being operated in a building.

Introduction

The radiant heating and cooling system consists of heat emitting/absorbing, heat supply, distribution, and control systems. The ISO 11855 series deals with the embedded surface heating and cooling system that directly controls heat exchange within the space. It does not include the system equipment itself, such as heat source, distribution system and controller.

The ISO 11855 series addresses an embedded system that is integrated with the building structure. Therefore, the panel system with open air gap, which is not integrated with the building structure, is not covered by this series.

The ISO 11855 series shall be applied to systems using not only water but also other fluids or electricity as a heating or cooling medium.

The object of the ISO 11855 series is to provide criteria to effectively design embedded systems. To do this, it presents comfort criteria for the space served by embedded systems, heat output calculation, dimensioning, dynamic analysis, installation, operation, and control method of embedded systems.

Building environment design — Design, dimensioning, installation and control of embedded radiant heating and cooling systems —

Part 4: Dimensioning and calculation of the dynamic heating and cooling capacity of Thermo Active Building Systems (TABS)

1 Scope

This part of ISO 11855 allows the calculation of peak cooling capacity of Thermo Active Building Systems (TABS), based on heat gains, such as solar gains, internal heat gains, and ventilation, and the calculation of the cooling power demand on the water side, to be used to size the cooling system, as regards the chiller size, fluid flow rate, etc.

This part of ISO 11855 defines a detailed method aimed at the calculation of heating and cooling capacity in non-steady state conditions.

The ISO 11855 series is applicable to water based embedded surface heating and cooling systems in residential, commercial and industrial buildings. The methods apply to systems integrated into the wall, floor or ceiling construction without any open air gaps. It does not apply to panel systems with open air gaps which are not integrated into the building structure.

The ISO 11855 series also applies, as appropriate, to the use of fluids other than water as a heating or cooling medium. The ISO 11855 series is not applicable for testing of systems. The methods do not apply to heated or chilled ceiling panels or beams.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 11855-1, *Building environment design — Design, dimensioning, installation and control of embedded radiant heating and cooling systems — Part 1: Definition, symbols, and comfort criteria*

3 Terms and definitions

For the purposes of this document, the terms and definitions in ISO 11855-1 apply.

4 Symbols and abbreviations

For the purposes of this part of ISO 11855, the symbols and abbreviations in Table 1 apply:

Table 1 — Symbols and abbreviations

Symbol	Unit	Quantity
A_F	m^2	Area of the heating/cooling surface area
A_W	m^2	Total area of internal vertical walls (i.e. vertical walls, external façades excluded)
C	$J/(m^2 \cdot K)$	Specific thermal capacity of the thermal node under consideration
C_W	$J/(m^2 \cdot K)$	Average specific thermal capacity of the internal walls
c_j	$J/(kg \cdot K)$	Specific heat of the material constituting the j-th layer of the slab
c_w	$J/(kg \cdot K)$	Specific heat of water
d_a	m	External diameter of the pipe
E_{Day}	kWh/m^2	Specific daily energy gains
f_{rm}^{h}	-	Running mode (1 when the system is running; 0 when the system is switched off) in the h-th hour
f_s	-	Design safety factor
$F_{v\ F\text{-}C}$	-	View factor between the floor and the ceiling
$F_{v\ F\text{-}EW}$	-	View factor between the floor and the external walls
$F_{v\ F\text{-}W}$	-	View factor between the floor and the internal walls
$h_{A\text{-}C}$	$W/(m^2 \cdot K)$	Convective heat transfer coefficient between the air and the ceiling
$h_{A\text{-}F}$	$W/(m^2 \cdot K)$	Convective heat transfer coefficient between the air and the floor
$h_{A\text{-}W}$	$W/(m^2 \cdot K)$	Convective heat transfer coefficient between the air and the internal walls
$h_{F\text{-}C}$	$W/(m^2 \cdot K)$	Radiant heat transfer coefficient between the floor and the ceiling
$h_{F\text{-}W}$	$W/(m^2 \cdot K)$	Radiant heat transfer coefficient between the floor and the internal walls
H_A	W/K	Heat transfer coefficient between the thermal node under consideration and the air thermal node (“A”)
H_C	W/K	Heat transfer coefficient between the thermal node under consideration and the ceiling surface thermal node (“C”)
$H_{Circuit}$	W/K	Heat transfer coefficient between the thermal node under consideration and the circuit
$H_{CondDown}$	W/K	Heat transfer coefficient between the thermal node under consideration and the next one
H_{CondUp}	W/K	Heat transfer coefficient between the thermal node under consideration and the previous one
H_{Conv}	-	Fraction of internal convective heat gains acting on the thermal node under consideration
H_F	W/K	Heat transfer coefficient between the thermal node under consideration and the floor surface thermal node (“F”)
$H_{Inertia}$	W/K	Coefficient connected to the inertia contribution at the thermal node under consideration
H_{IWS}	W/K	Heat transfer coefficient between the thermal node under consideration and the internal wall surface thermal node (“IWS”)
H_{Rad}	-	Fraction of total radiant heat gains impinging on the thermal node under consideration
h_t	$W/(m^2 \cdot K)$	Total heat transfer coefficient (convection + radiation) between surface and space
J	-	Number of layers constituting the slab as a whole

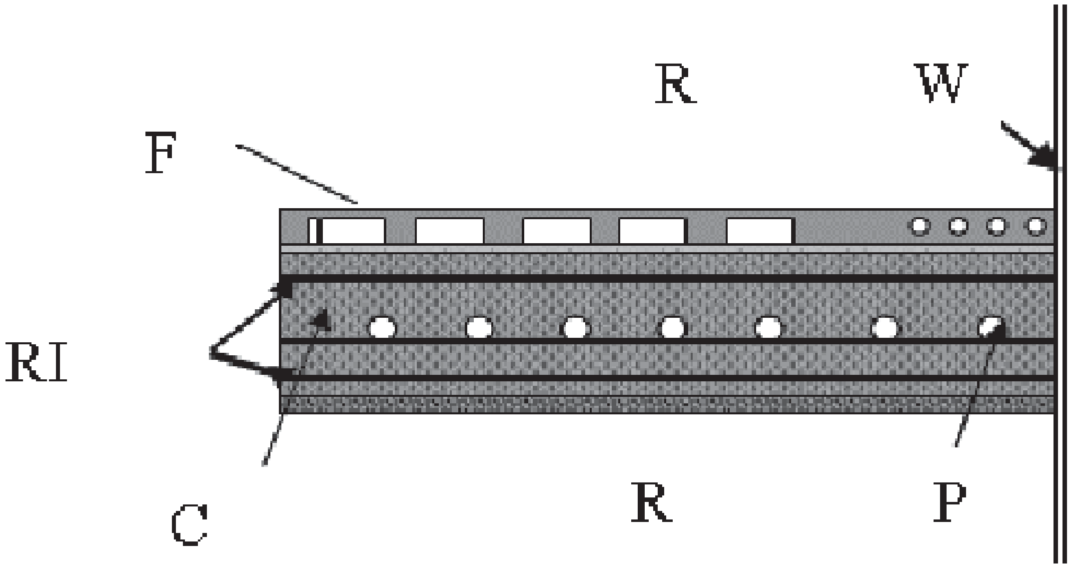
Symbol	Unit	Quantity
J_1	-	Number of layers constituting the upper part of the slab
J_2	-	Number of layers constituting the lower part of the slab
L_R	m	Length of installed pipes
$\dot{m}_{H,sp}$	kg/(m²·s)	Specific water flow in the circuit, calculated on the area covered by the circuit
m_j	-	Number of partitions of the j-th layer of the slab
n	-	Actual number of iteration in iterative calculations
n_h	h	Number of operation hours of the circuit
n^{Max}	-	Maximum number of iterations allowed in iterative calculations
$P_{Circuit}^{Max,h}$	W	Maximum cooling power reserved to the circuit under consideration in the h-th hour
$P_{Circuit,Spec}^{Max}$	W/m²	Maximum specific cooling power (per floor square metre)
q_i	W/m²	Inward specific heat flow
q_u	W/m²	Outward specific heat flow
Q_C^h	W	Heat flow impinging on the ceiling surface (“C”) in the h-th hour
$Q_{Circuit}^h$	W	Heat flow extracted by the circuit in the h-th hour
Q_{Conv}^h	W	Total convective heat gains in the h-th hour
Q_F^h	W	Heat flow impinging on the floor surface (“F”) in the h-th hour
$Q_{IntConv}^h$	W	Internal convective heat gains in the h-th hour
Q_{IntRad}^h	W	Internal radiant heat gains in the h-th hour
Q_{IWS}^h	W	Heat flow impinging on the internal wall surface (“IWS”) in the h-th hour
$Q_{PrimAir}^h$	W	Primary air convective heat gains in the h-th hour
Q_{Rad}^h	W	Total radiant heat gains in the h-th hour
Q_{Sun}^h	W	Solar heat gains in the room in the h-th hour
Q_{Transm}^h	W	Transmission heat gains in the h-th hour
Q_W	W/m²	Average specific cooling power
R	(m²·K)/W	Generic thermal resistance
$R_{Add\ C}$	(m²·K)/W	Additional thermal resistance covering the lower side of the slab
$R_{Add\ F}$	(m²·K)/W	Additional thermal resistance covering the upper side of the slab
$RCAC$	K/W	Convection thermal resistance connecting the air thermal node (“A”) with the ceiling surface thermal node (“C”)
$RCAF$	K/W	Convection thermal resistance connecting the air thermal node (“A”) with the floor surface thermal node (“F”)
$RCAW$	K/W	Convection thermal resistance connecting the air thermal node (“A”) with the internal wall surface thermal node (“IWS”)

Symbol	Unit	Quantity
R_{int}	(m²·K)/W	Internal thermal resistance of the slab conductive region
$R_{L,p}$	(m²·K)/W	Conduction thermal resistance connecting the p-th thermal node with the boundary of the (p+1)-th thermal node
R_r	(m²·K)/W	Pipe thickness thermal resistance
$RRFC$	K/W	Radiation thermal resistance connecting the floor surface thermal node ("F") with the ceiling surface thermal node ("C")
$RRWC$	K/W	Radiation thermal resistance connecting the internal wall surface thermal node ("IWS") with the ceiling surface thermal node ("C")
$RRWF$	K/W	Radiation thermal resistance connecting the internal wall surface thermal node ("IWS") with the floor surface thermal node ("F")
R_t	(m²·K)/W	Circuit total thermal resistance
$R_{U,p}$	(m²·K)/W	Conduction thermal resistance connecting the p-th thermal node with the boundary of the (p-1)-th thermal node
R_{Walls}	(m²·K)/W	Wall surface thermal resistance
R_w	(m²·K)/W	Water flow thermal resistance
R_x	(m²·K)/W	Pipe level thermal resistance
R_z	(m²·K)/W	Convection thermal resistance at the pipe inner side
s_r	m	Pipe wall thickness
s_1	m	Thickness of the upper part of the slab
s_2	m	Thickness of the lower part of the slab
W	m	Pipe spacing
δ_j	m	Thickness of the j-th layer of the slab
$\Delta\theta$	K	Generic temperature difference
$\Delta\theta_{Comfort}^{Max}$	K	Maximum operative temperature drift allowed for comfort conditions
Δt	s	Calculation time step
θ_A^h	°C	Temperature of the air thermal node ("A") in the h-th hour
θ_C^h	°C	Temperature of the ceiling surface thermal node ("C") in the h-th hour
$\theta_{Comfort}^{Max}$	°C	Maximum operative temperature allowed for comfort conditions
$\theta_{Comfort,Ref}$	°C	Maximum operative temperature allowed for comfort conditions in the reference case
θ_F^h	°C	Temperature of the floor surface thermal node ("F") in the h-th hour
θ_{IW}^h	°C	Temperature of the core of the internal walls thermal node ("IW") in the h-th hour
θ_{IWS}^h	°C	Temperature of the internal wall surface thermal node ("IWS") in the h-th hour
θ_{MR}^h	°C	Room mean radiant temperature in the h-th hour
θ_{Op}^h	°C	Room operative temperature in the h-th hour

Symbol	Unit	Quantity
θ_{p}^{h}	°C	Temperature of the p-th thermal node in the h-th hour
θ_{PL}^{h}	°C	Temperature of the pipe level thermal node (“PL”) in the h-th hour
θ_{Slab}^{Av}	°C	Daily average temperature of the conductive region of the slab
$\theta_{Water,In}^{h}$	°C	Water inlet actual temperature in the h-th hour
$\theta_{Water,In}^{Setp,h}$	°C	Water inlet set-point temperature in the h-th hour
$\theta_{Water,In,Ref}^{Setp}$	°C	Water inlet set-point temperature in the reference case
$\theta_{Water,Out}^{h}$	°C	Water outlet temperature in the h-th hour
λ_{b}	W/(m·K)	Thermal conductivity of the material of the pipe embedded layer
λ_{j}	W/(m·K)	Thermal conductivity of the material constituting the j-th layer of the slab
λ_{r}	W/(m·K)	Thermal conductivity of the material constituting the pipe
ξ	K	Actual tolerance in iterative calculations
ξ_{Max}	K	Maximum tolerance allowed in iterative calculations
ρ_{j}	kg/m^3	Density of the material constituting the j-th layer of the slab
ω	various	Slope of correlation curves

5 The concept of Thermally Active Surfaces (TAS)

A Thermally Active Surface (TAS) is an embedded water based surface heating and cooling system, where the pipe is embedded in the central concrete core of a building construction (see Figure 1).

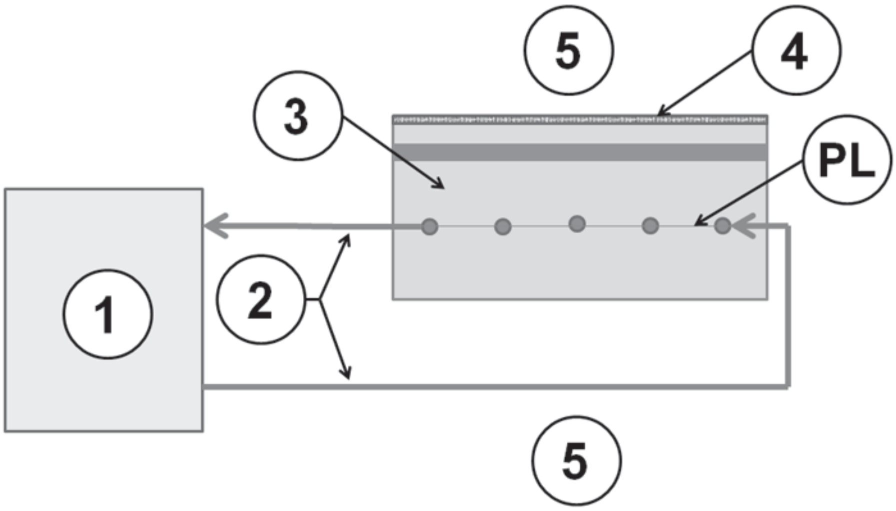


Key

C concrete
F floor
P pipes
R room
RI reinforcement
W window

Figure 1 — Example of position of pipes in TAS

The building constructions embedding the pipe are usually the horizontal ones. As a consequence, in the following sections, floors and ceilings are usually referred to as active surfaces. Looking at a typical structure of a TAS, heat is removed by a cooling system (for instance, a chiller), connected to pipes embedded in the slab. The system can be divided into the elements shown in Figure 2.

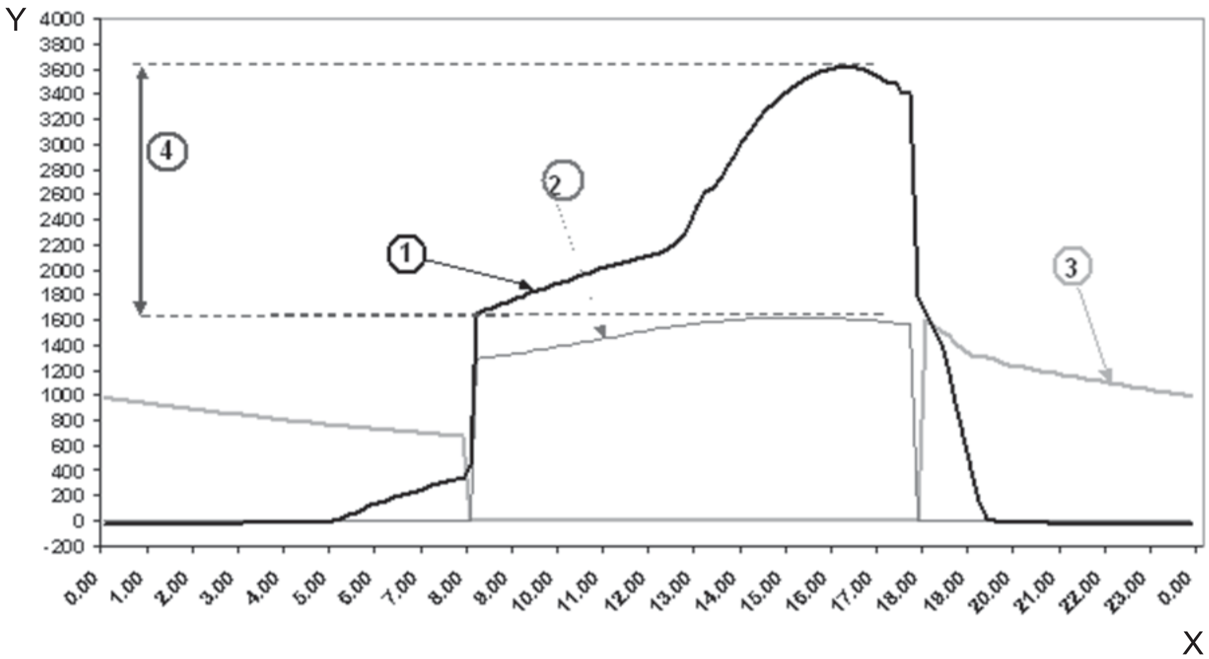


Key

1 heating/cooling equipment
2 hydraulic circuit
3 slab including core layer with pipes
4 possible additional resistances (floor covering or suspended ceiling)
5 room below and room above
PL pipe level

Figure 2 — Simple scheme of a TAS

Thermally active surfaces exploit the high thermal inertia of the slab in order to perform the peak-shaving. The peak-shaving consists in reducing the peak in the required cooling power (see Figure 3), so that it is possible to cool the structures of the building during a period in which the occupants are absent (during night time, in office premises). This way the energy consumption can be reduced and a lower night time electricity rate can be used. At the same time a reduction in the size of heating/cooling system components (including the chiller) is possible.



Key

X time, h

Y cooling power, W

1 heat gain

2 cooling power needed for conditioning the ventilation air

3 cooling power needed on the water side

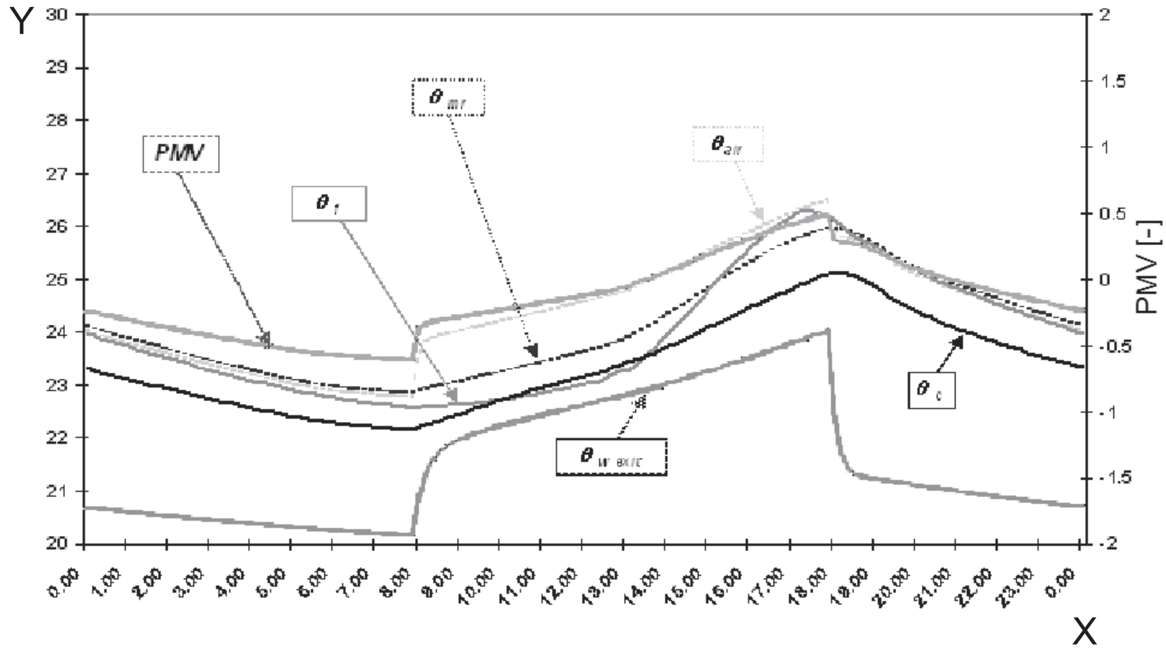
4 reduction of the required peak power

Figure 3 — Example of peak-shaving effect

TABS may be used both with natural and mechanical ventilation (depending on weather conditions). Mechanical ventilation with dehumidifying may be required depending on external climate and indoor humidity production. In the example in Figure 3, the required peak cooling power needed for dehumidifying the air during day time is sufficient to cool the slab during night time.

As regards the design of TABS, the planner needs to know if the capacity at a given water temperature is sufficient to keep the room temperature within a given comfort range. Moreover, the planner needs also to know the heat flow on the water side to be able to dimension the heat distribution system and the chiller/boiler. This part of ISO 11855 provides methods for both purposes.

When using TABS, the indoor temperature changes moderately during the day and the aim of a good TABS design is to maintain internal conditions within the range of comfort, i.e. –0,5 < PMV < 0,5, during the day, according to ISO 7730 (see Figure 4).



Key

X	time, h
Y	temperature, °C
PMV	Predicted Mean Vote
θ_{air}	air temperature
θ_{c}	ceiling temperature
θ_{mr}	mean radiant temperature
θ_{f}	floor temperature
$\theta_{w\ exit}$	water return temperature

Figure 4 — Example of temperature profiles and PMV values vs. time

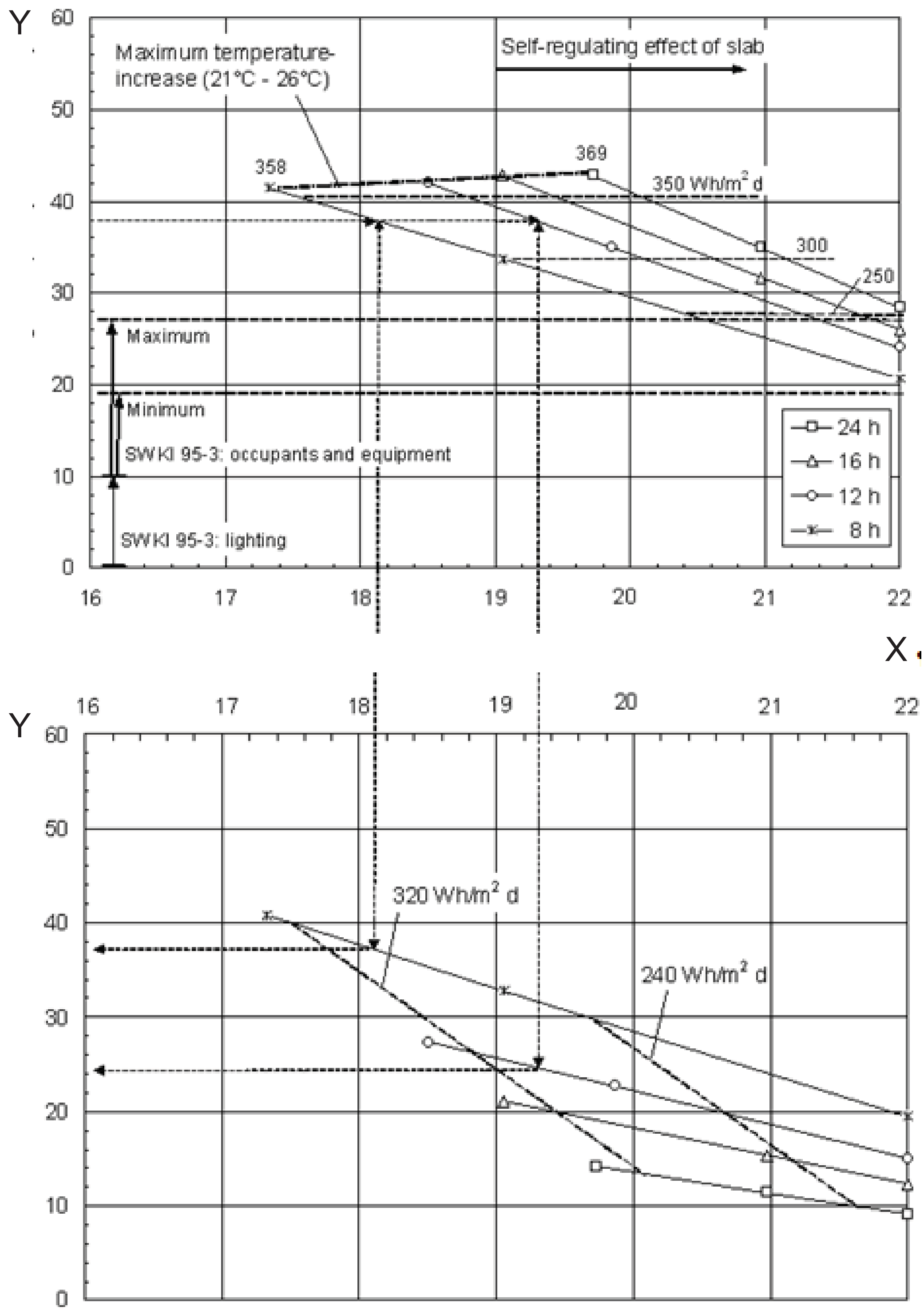
Some detailed building system calculation models have been developed to determine the heat exchanges under unsteady state conditions in a single room, the thermal and hygrometric balance of the room air, prediction of comfort conditions, check of condensation on surfaces, availability of control strategies and calculation of the incoming solar radiation. The use of such detailed calculation models is, however, limited due to the high amount of time needed for the simulations. The development of a more user friendly tool is required. Such a tool is provided in this part of ISO 11855, and allows the simulation of TAS.

The diagrams in Figure 5 show an example of the relation between internal heat gains, water supply temperature, heat transfer on the room side, hours of operation and heat transfer on the water side. The diagrams refer to a concrete slab with raised floor (R = 0,45 (m^2·K)/W) and an allowed room temperature range of 21°C to 26°C.

The upper diagram shows on the Y-axis the maximum permissible total heat gain in space (internal heat gains plus solar gains) [W/m^2], and on the X-axis the required water supply temperature. The lines in the diagram correspond to different operation periods (8 h, 12 h, 16 h, and 24 h) and different maximum amounts of energy supplied per day [Wh/(m^2·d)].

The lower diagram shows the cooling power [W/m^2] required on the water side (to dimension the chiller) for TAS as a function of supply water temperature and operation time. Further, the amount of energy rejected per day is indicated [Wh/(m^2·d)].

The example shows that, for a maximum internal heat gain of 38 W/m^2 and 8 h operation, a supply water temperature of 18,2 °C is required. If, instead, the system is in operation for 12 h, a supply water temperature of 19,3 °C is required. In total, the amount of energy rejected from the room is approximately 335 Wh/m^2 per day. In the same conditions, the required cooling power on the water side is 37 W/m^2 (for 8 h operation) and 25 W/m^2 (for 12 h operation) respectively. Thus, by 12 h operation, the chiller can be much smaller.



Key

X (upper diagram) inlet temperature tabs, °C

Y (upper diagram) maximum total heat gain in space (W/m^2, floor area)

Y (lower diagram) mean cooling power tabs (W/m^2, floor area)

Figure 5 — Working principle of TABS

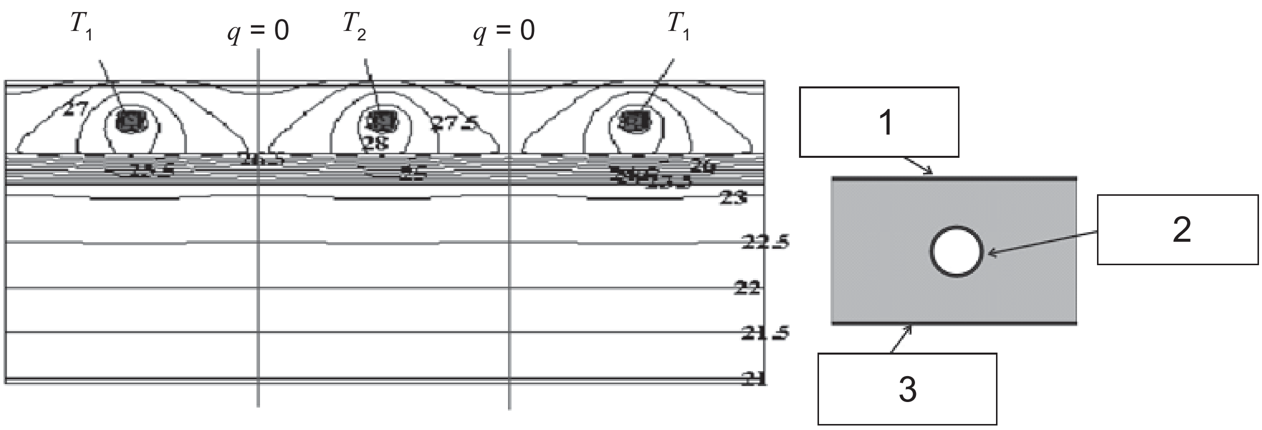
6 Calculation methods

6.1 General

TABS are systems with high thermal inertia. Therefore, for sizing chillers coupled with them, dynamic simulations have to be carried out. In principle, the solution of heat transfer inside structures with embedded pipes has to deal with 2-D calculations (see Figure 6). The calculation time required to consider the 2-D thermal field and the overall balance with the rest of the room is usually too high. Therefore, mathematical models in literature are usually based on a link between the pipe surface and the upper and lower surfaces (i.e. floor and ceiling).

One possibility to model radiant systems is to apply response factors to the pipe surface, upper surface and lower surface of the slab (see Figure 7). This way, the conduction heat transfer is defined via nine response factor series, that can be reduced to six response factor series, because of reciprocity rules.

*H*p: $T_1 = T_2 = T_3$



Key

1 upper surface

2 pipe surface

3 lower surface

Figure 6 — Heat transfer through structures containing pipes

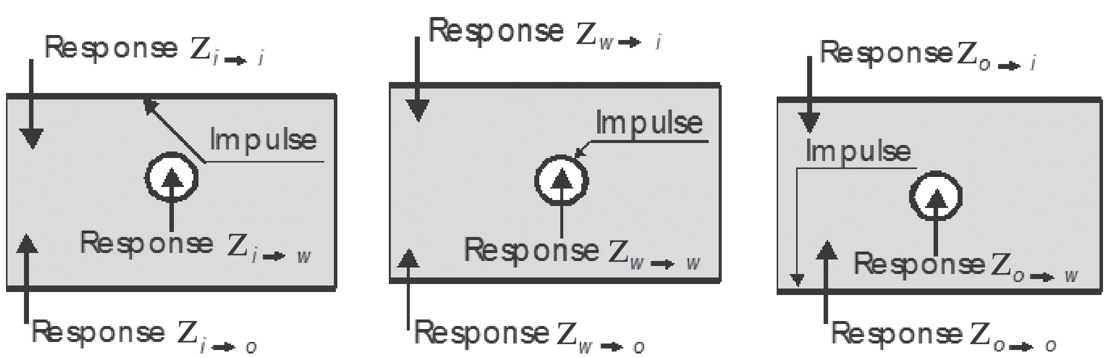
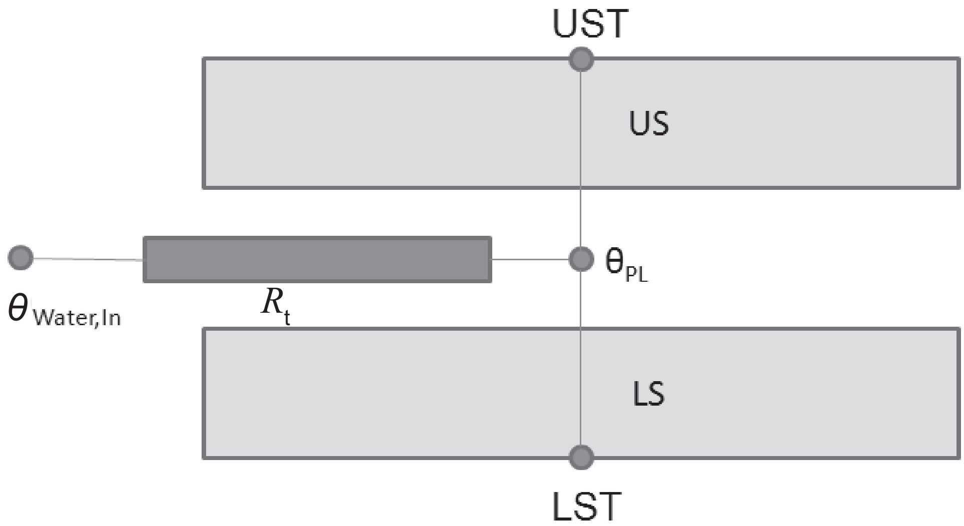


Figure 7 — Transfer functions for building elements containing pipes

Another possibility is to consider a resistance between the external pipe surface and an equivalent core temperature at pipe level, which represents the average temperature along the axial plane of the pipes (see Figure 8). From the core level to upward and downward levels, a 1-D resistance-capacity network or 1-D response factor series (or transfer function) can be applied.



Key

LS	lower part of the slab
LST	lower surface temperature (ceiling)
R_t	circuit total thermal resistance
US	upper part of the slab
UST	upper surface temperature (floor)
θ_{PL}	mean temperature at the pipe level
$\theta_{Water,In}$	water supply temperature

Figure 8 — Simplified model for the conductive heat transfer in a structure containing pipes

In this part of ISO 11885, the following calculation methods are presented:

— Rough sizing method, based on a standard calculation of the cooling load (error: 20÷30%). To be used starting from the knowledge of the daily heat gains in the room (see 6.2).

— Simplified method using diagrams for sizing, based on the knowledge of the total energy to be extracted daily to ensure comfort conditions (error: 15÷20%). For details, see 6.3.

— Simplified model based on finite difference method (FDM) (error: 10÷15%). It consists in detailed dynamic simulations predicting the heat transfers in the slab and even in the room via FDM. Based on the knowledge of the values of the variable cooling loads of the room during each hour of the day. For further details, see 6.4.

— Detailed simulation models (error: 6÷10%). It implies the overall dynamic simulation model for the radiant system and the room via detailed building-system simulation software (see 6.5).

6.2 Rough sizing method

The cooling system shall be sized via the following equation:

$$P_{\text{Circuit,Spec}}^{\text{Max}} = \frac{E_{\text{Day}}}{n_{\text{h}}} \cdot 1000 \cdot f_{\text{s}} \qquad [\text{W/m}^2] \tag{1}$$

where

$P_{\text{Circuit,Spec}}^{\text{Max}}$ is the maximum specific cooling power (per floor square metre) [W/m^2];

E_{Day} is the specific daily energy gains [kWh/m^2];

n_{h} is the number of operation hours of the circuit [h];

f_{s} is the safe design factor (greater than one, usually 1,15) [-].

For this purpose, E_{Day} shall be calculated in the following way:

— The hourly values of heat gains are calculated for the room under the design conditions and occupancy schedules, via an energy simulation tool or a proper method for the calculation of heat gains.

— E_{Day} is the sum of the 24 values of heat gains.

The heat gains calculation has to be carried out using an operative temperature 0,5°C lower than the average operative temperature during occupancy hours, for the sake of safe design. As a consequence, if the room operative temperature drift during occupancy hours is 21,0°C to 26,0°C, then the room average operative temperature during occupancy hours is 23,5°C, and the reference room operative temperature for the calculation of heat gains is 23,0°C.

6.3 Simplified sizing by diagrams

In this case, the calculation of the heat gains has to be carried out by means of the value of the total cooling energy to be provided during the day in order to ensure comfort conditions at the average operative temperature (for instance, 23,0°C). This method is based on the assumption that the entire thermally conductive part of the slab is maintained at an almost constant temperature during the whole day, due to its own thermal inertia and the thermal resistance dividing it from the rooms over and below. This average temperature of the slab is calculated by the method itself and is used to calculate the water supply temperature depending on the running time of the circuit.

The following magnitudes are involved in this method:

— E_{Day} : specific daily energy gains in the room during the design day: it consists of the sum of heat gains values acting during the whole design day, divided by the floor area [kWh/m^2].

— $\theta_{\text{Comfort}}^{\text{Max}}$: maximum operative room temperature allowed for comfort conditions [°C].

— Orientation of the room: used to determine when the peak load in heat gains happens: east (morning), south (noon) or west (afternoon).

— Number of active surfaces: distinguishes whether the slab works transferring heat both through the floor side and through the ceiling side or just through the ceiling side (see Figure 9).

— n_{h} : number of operation hours of the circuit [h].

— R_{Int} : internal thermal resistance of the slab conductive region [(m^2·K)/W]. It is the average thermal resistance that connects the conductive parts of the slab placed near the pipe level to the pipe level itself (see Figure 12).

— $\theta_{\text{Slab}}^{\text{Av}}$: daily average temperature of the conductive region of the slab [°C]. It is a result of the present method and depends on the number of active surfaces (ceiling only, or ceiling and floor), the running mode (24 h or 8 h) and the shape of the internal load profile (lunch break or not) and room orientation. The average temperature of the slab is achieved through coefficients included in the method by the equation.

$$\theta_{\text{Slab}}^{\text{Av}} = \theta_{\text{Comfort}}^{\text{Max}} + \omega \cdot E_{\text{Day}} \qquad [°\text{C}] \tag{2}$$

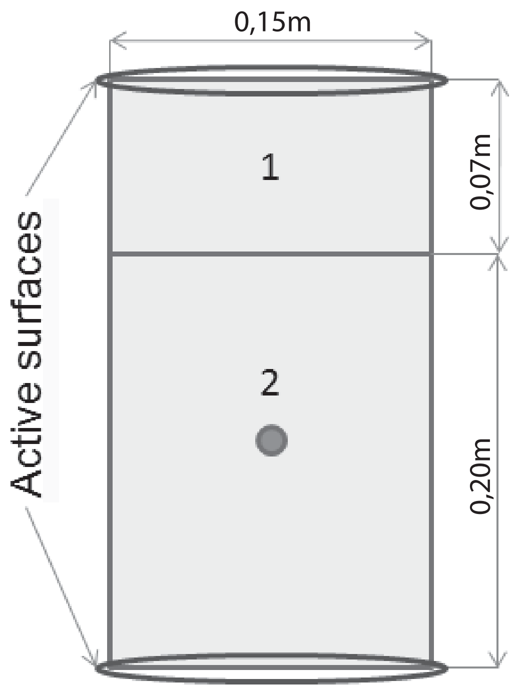
where ω is a coefficient, whose values are given in Tables 1 and 2.

— R_{t} : circuit total thermal resistance, obtained via the Resistance Method (for further details, see ISO 11855-2) [(m^2·K)/W]. This thermal resistance depends on the characteristics of the circuit, pipe, and conductive slab (see Figure 14).

— $\theta_{\text{Water,In}}^{\text{Setp}}$: water supply temperature required for ensuring comfort conditions [°C].

It is obtained through the following equation:

$$\theta_{\text{Water,In}}^{\text{Setp}} = \theta_{\text{Slab}}^{\text{Av}} - \left(\frac{E_{\text{Day}} \cdot 1000}{h}\right) \cdot \left(R_{\text{int}} + R_{\text{t}}\right) \qquad [°\text{C}] \tag{3}$$



Key

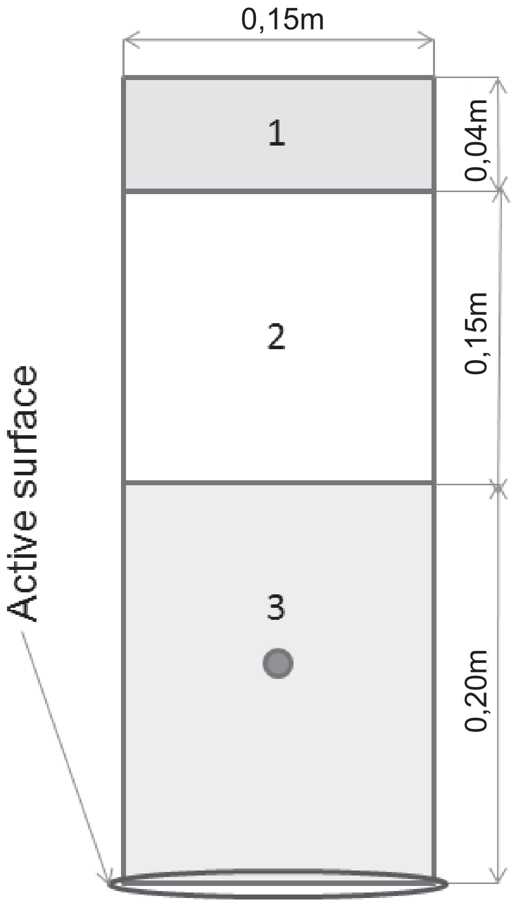
1 concrete

2 reinforced concrete

Conductive region: Material 1 and Material 2

Number of active surfaces: 2

Figure 9 — Example 1 — Conductive regions and numbers of active surfaces



Key

1 wood

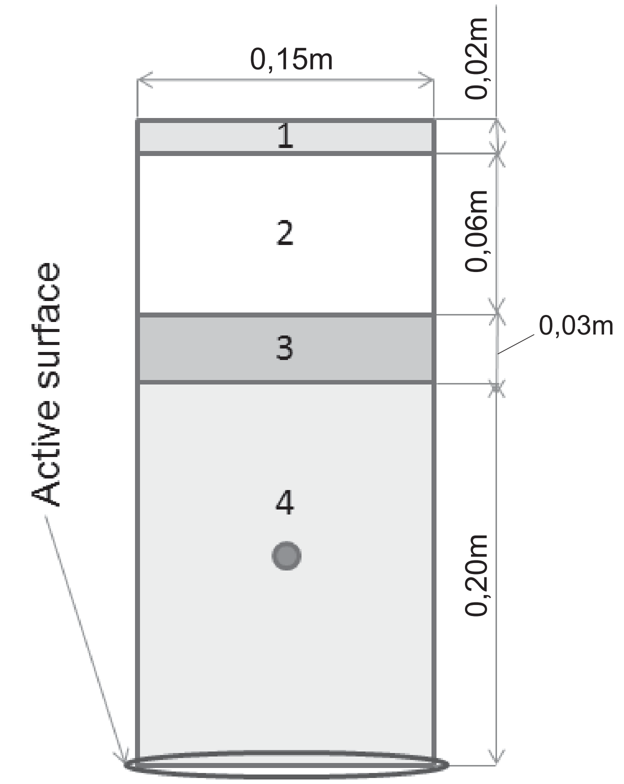
2 air

3 reinforced concrete

Conductive region: Material 3

Number of active surfaces: 1

Figure 10 — Example 2 — Conductive regions and numbers of active surfaces



Key

1 wood

2 concrete

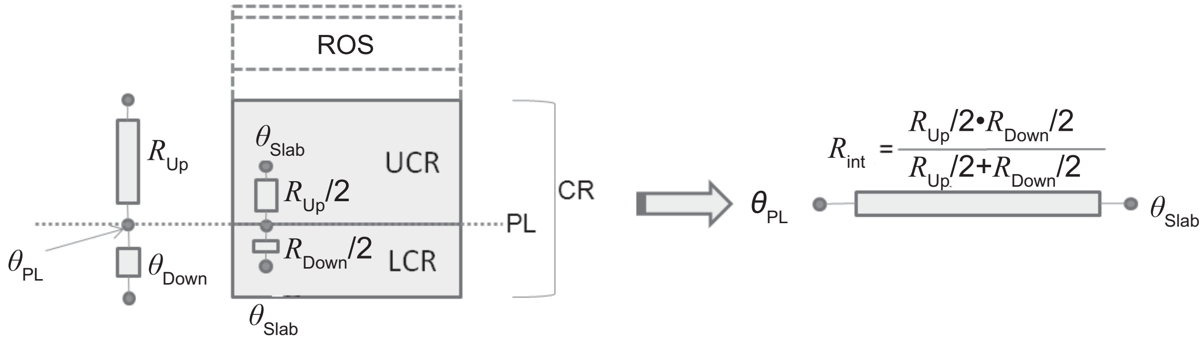
3 fibreglass

4 reinforced concrete

Conductive region: Material 4

Number of active surfaces: 1

Figure 11 — Example 3 — Conductive regions and numbers of active surfaces



Key

CR	conductive region
LCR	lower part of the slab conductive region
PL	pipe level
R_{Down}	total thermal resistance of the lower part of the slab conductive region
R_{int}	internal thermal resistance of the slab conductive region
R_{Up}	total thermal resistance of the upper part of the slab conductive region
ROS	rest of the slab
UCR	upper part of the slab conductive region
θ_{PL}	average daily temperature at the pipe level
θ_{slab}	average daily temperature of the conductive region of the slab

Figure 12 — Thermal resistance network equivalent to the slab conductive region in simplified sizing by diagrams

The coefficients suggested for the calculation of the average temperature of the conductive region of the slab are given in Tables 2 and 3, depending on the shape of the internal heat gain profile. For intermediate duration (e.g. a lunch break), a correspondent interpolation between coefficients of Table 2 and Table 3 is recommended.

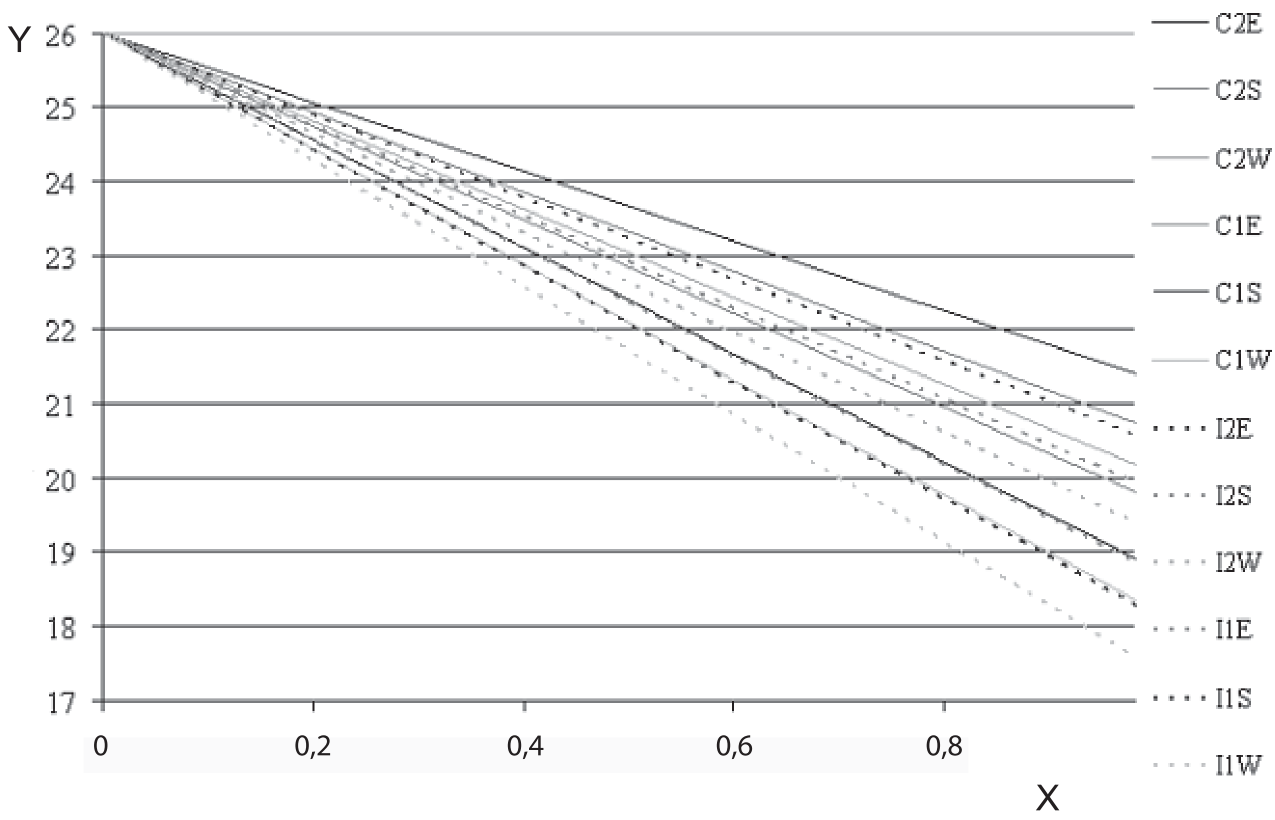
Table 2 — Constant internal heat gains from 8:00 to 18:00

Circuit running mode	Number of active surfaces	Orientation of the room		
		East (E)	South (S)	West (W)
		ω		
Continuous (24 h)	Floor and ceiling (C2)	-4,6 816	-5,3 696	-5,935
	Only ceiling (C1)	-6,3 022	-7,2 237	-7,7 982
Intermittent (8 h)	Floor and ceiling (I2)	-5,5 273	-6,1 701	-6,7 323
	Only ceiling (I1)	-7,2 853	-7,8 562	-8,5 791

Table 3 — Constant internal heat gains from 8:00 to 12:00 and from 14:00 to 18:00

Circuit running mode	Number of active surfaces	Orientation of the room		
		East (E)	South (S)	West (W)
		ω		
Continuous (24 h)	Floor and ceiling (C2)	-6,279	-7,1 094	-7,3 681
	Only ceiling (C1)	-7,9 663	-8,7 989	-8,7 455
Intermittent (8 h)	Floor and ceiling (I2)	-8,1 474	-8,758	-9,3 264
	Only ceiling (I1)	-10,029	-10,685	-10,967

By the choice of $\theta_{\text{Comfort}}^{\text{Max}}$, it is possible to adapt the method to different maximum room operative temperatures, if the same maximum operative temperature drift allowed for comfort conditions is kept. Once $\theta_{\text{Comfort}}^{\text{Max}}$ is defined, the tables can be summarized by diagrams. For example, if $\theta_{\text{Comfort}}^{\text{Max}}$ = 26°C, the diagram for constant internal heat gains from 8:00 to 18:00 is as given in Figure 13.



Key

X $E_{\text{Day,}}$ °C

Y $\theta_{\text{slab,}}$ kWh/m^2

Figure 13 — Diagram for determining θ_{slab} as a function of the specific daily energy, exposure of the room (E = east, S = south, W = west), running mode of the circuit (C = continuous - 24 h, I = intermittent - 8 h), and number of active surfaces (1 or 2), in the case of constant internal heat gains during the day

Example

Input data

— E_{Day} : 0,6 kWh/m²;

— Shape of thermal loads: no lunch break;

— $\theta_{Comfort}^{Max}$: 26°C;

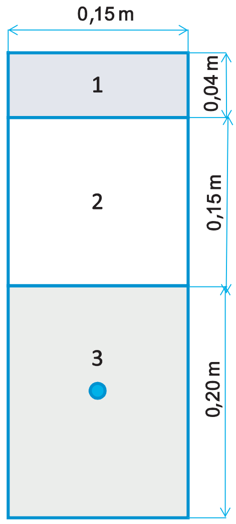
— Exposure of the room: south;

— n_h: 24 h;

— Thermal conductivity of the conductive region of the slab: 1,9 W/(m·K);

— R_t: 0,07 (m²·K)/W;

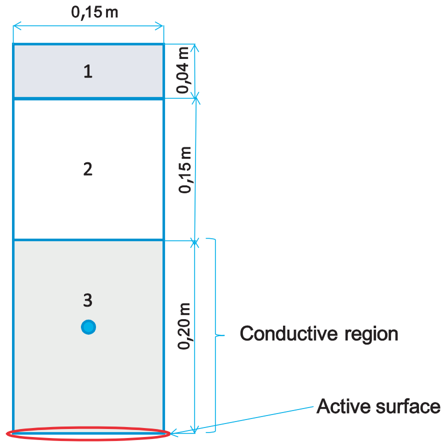
— Kind of floor:



Key:
1 wood
2 air
3 reinforced concrete

Main calculation steps

Individuation of the conductive region and number of active surfaces:



— Calculation of R_{int}:

— R_{up} = R_{down} = 0,1/1,9 = 0,053 (m²·K)/W

— ⇨R_{int} = 0,0 265 (m²·K)/W

— Determination of ω (from Table 1): –7,2 237 (m²·K)/kWh

$$\theta_{Slab}^{Av} = 26{,}0 - 7{,}2\,237 \cdot 0{,}6 = 21{,}7°C$$

$$\theta_{Water,In}^{Setp} = 21{,}7 - \frac{0{,}6 \cdot (0{,}0\,265 + 0{,}07) \cdot 1000}{24} = 19{,}3°C$$

6.4 Simplified model based on FDM

The model is based on the calculation of the heat balance for each thermal node defined within the slab and the room. The slab and the room are divided into thermal nodes used to calculate the main heat flows taking place during the day. The temperature of each thermal node during the hour under consideration depends on the temperatures of the other thermal nodes during the same hour. As a consequence, the heat balances of all the thermal nodes would require the solution via a system of equations, or an iterative solution. The last option is the one chosen in this part of ISO 11885. As a consequence, most of the equations regarding this method (see also Annex B) apply for each iteration executed in order to approach the final solution. The use of an iterative method requires the definition of four quantities:

n: actual number of the current iteration [-];

n_{Max}: maximum number of iterations allowed [-];

ξ: actual tolerance at the current iteration [K];

ξ_{Max}: maximum tolerance allowed [K].

The actual number of the current iteration and the actual tolerance at the current iteration are calculated at each iteration and compared with the maximum number of iterations and tolerance allowed respectively. In particular, if $\xi < \xi_{Max}$ and $n < n_{Max}$, then the solution has been found within the given conditions. Instead, if $n >= n_{Max}$, then the number of iterations performed has been too high and the solution has not reached the given accuracy. That would require a higher value of n_{Max} or ξ_{Max}, in case a lower degree in accuracy can be accepted.

6.4.1 Cooling system

As regards the cooling equipment, it is simulated via the following magnitudes:

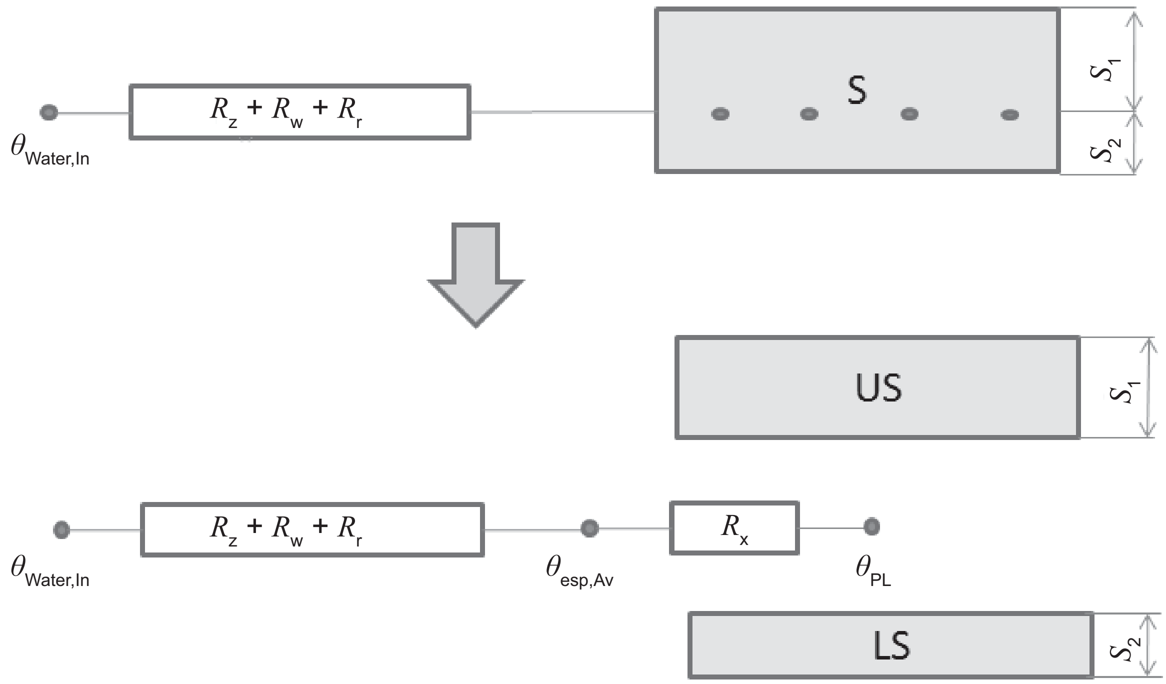
— $\theta_{Water,In}^{Setp,h}$: water inlet set-point temperature in the h-th hour [°C];

— $P_{Circuit}^{Max,h}$: maximum cooling power reserved to the circuit under consideration in the h-th hour [W].

The limited power of the cooling system shall be taken into account, since the chiller is able to keep a constant supply water temperature only when the heat flow extracted by the circuit is lower than the maximum cooling power expressed by the chiller. For further details, see Annex B.

6.4.2 Hydraulic circuit and slab

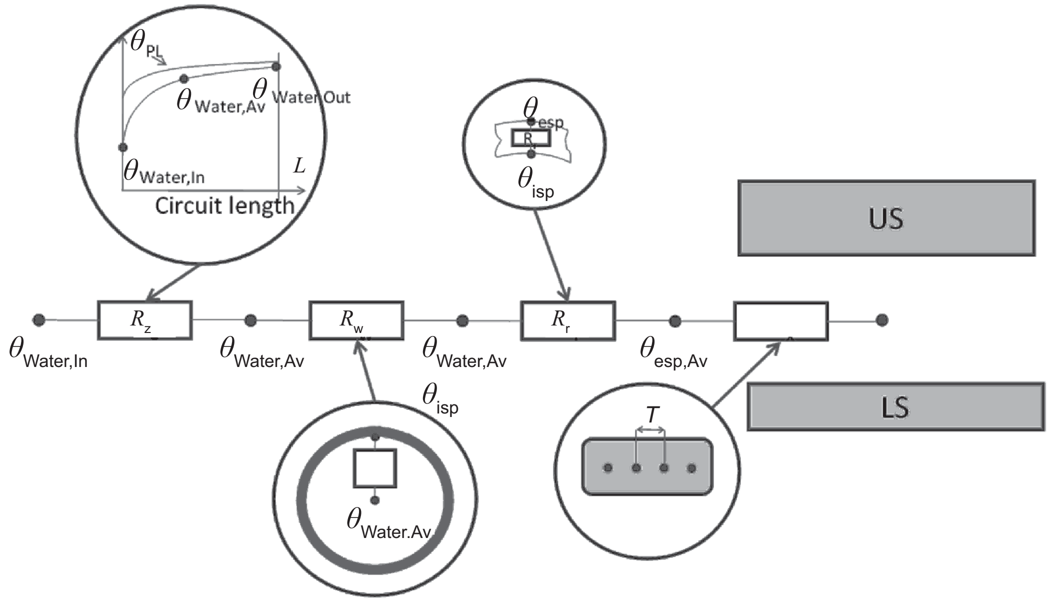
The Resistance Method (for further details, see ISO 11855-2) is applied. It sets up a straightforward relation, expressed in terms of resistances, between the water supply temperature and the average temperature at the pipe plane,θ_{PL} so that the slab can be split into two smaller slabs. In this way, the upper slab (which is above the pipe plane) and the lower slab (which is below the pipe plane) are considered separately (see Figures 14 and 15). Their thermal behaviour is analysed through an implicit FDM. For details about the calculation process, see Annex B.



Key

LS	lower part of the slab
R_r	pipe thickness thermal resistance
R_w	convection thermal resistance at the pipe inner side
R_x	pipe level thermal resistance
R_z	water flow thermal resistance
S	slab
S_1	thickness of the upper part of the slab
S_2	thickness of the lower part of the slab
US	upper part of the slab
$\theta_{esp,Av}$	average temperature at the outer side of the pipe
θ_{PL}	average temperature at the pipe level
$\theta_{Water,In}$	water inlet temperature

Figure 14 — Concept of the Resistance Method



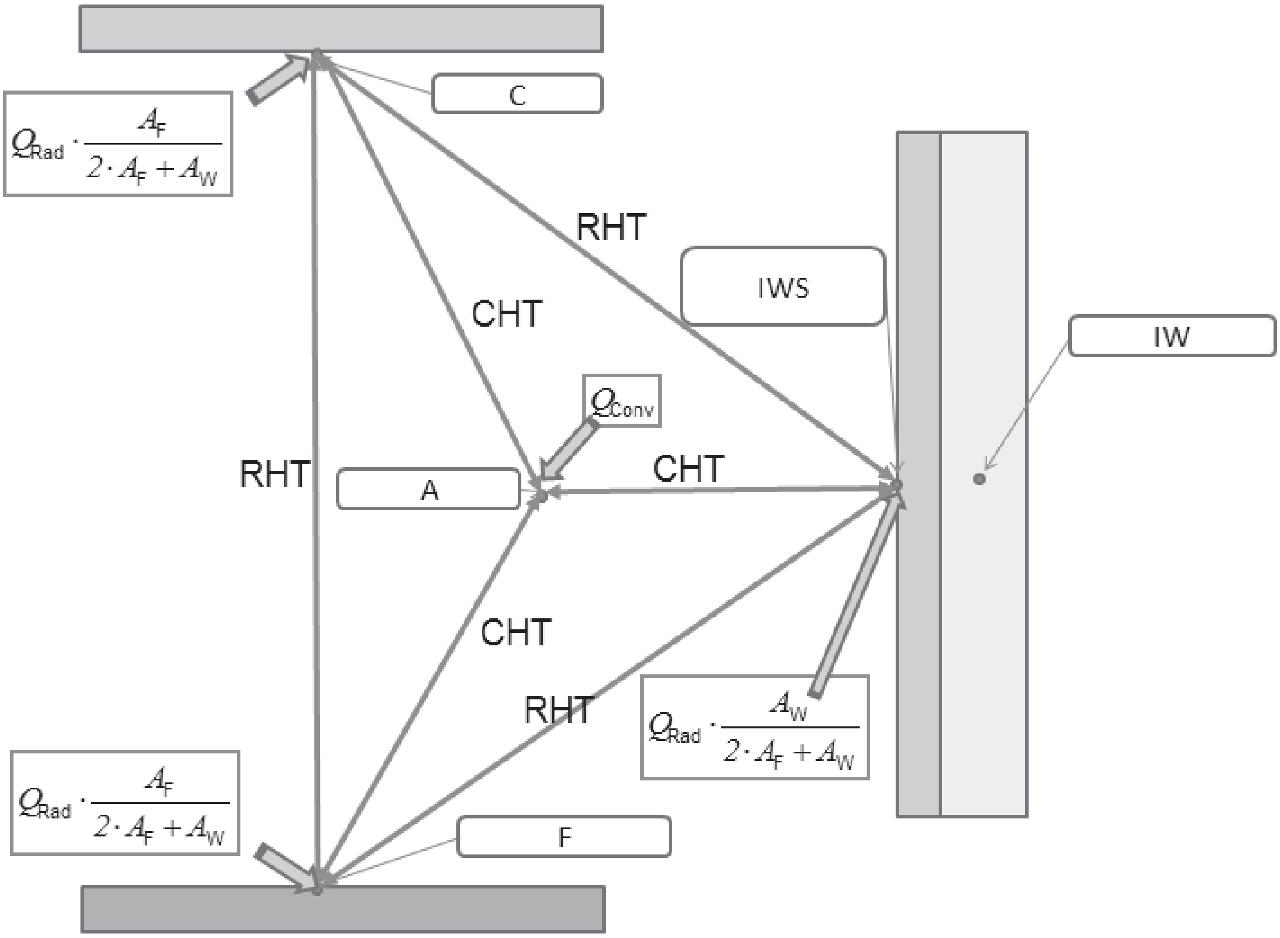
Key

L	length of installed pipes
LS	lower part of the slab
R_r	pipe thickness thermal resistance
R_w	convection thermal resistance at the pipe inner side
R_x	pipe level thermal resistance
R_z	water flow thermal resistance
T	pipe spacing
US	upper part of the slab
$\theta_{esp,Av}$	average temperature at the outer side of the pipe
$\theta_{isp,Av}$	average temperature at the inner side of the pipe
θ_{PL}	average temperature at the pipe level
$\theta_{Water,Av}$	water average temperature
$\theta_{Water,In}$	water inlet temperature
$\theta_{Water,Out}$	water outlet temperature

Figure 15 — General scheme of the Resistance Method

6.4.3 Room

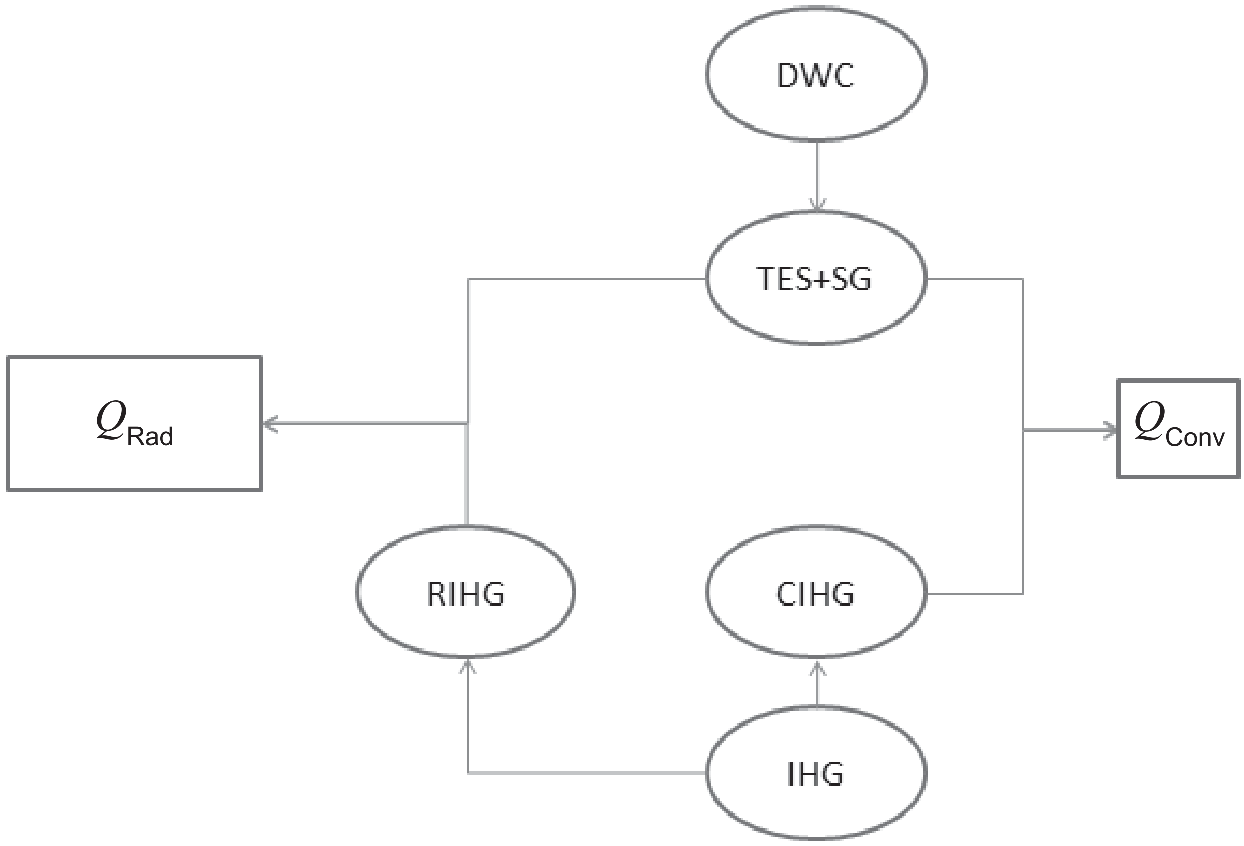
An air node is taken into account and connected with the upward and downward surface of the slab and with a fictitious thermal node at the wall surface. Two surfaces of the slab are connected to each other to take into account the radiation exchange between them, and finally each slab surface is connected to the wall surface node (see Figure 16). Moreover, hourly heat gains are distributed on air and surfaces, depending on their characteristics (see again Figure 16). The composition of heat gains is shown in Figure 17. For further details, see Annex B.



Key

A	thermal node representing the air in the room
C	thermal node representing the ceiling surface
CHT	convective heat transfer
F	thermal node representing the floor surface
IW	thermal node representing the internal walls
IWS	thermal node representing the internal wall surface
RHT	radiant heat transfer
Q_{Conv}	total convective heat gains
Q_{Rad}	total radiant heat gains

Figure 16 — Scheme of the thermal network representing the room



Key

CIHG convective internal heat gains
DWC design weather conditions
IHG internal heat gains
RIHG radiant internal heat gains
Q_{Conv} total convective heat gains
Q_{Rad} total radiant heat gains
SG solar gain
TES transmission through the external surfaces

Figure 17 — Heat loads acting in the room and how they take part in the calculations

6.4.4 Limits of the method

The following limitations shall be met:

— pipe spacing: from 0,15 m to 0,3 m;

— usual concrete slab structures have to be considered, λ = 1,15-2,00 W/(m·K), with upward additional materials, which might be acoustic insulation or raised floor. No discontinuous light fillings can be considered in the structures of the lower and upper slabs.

If these conditions are not fulfilled, a detailed simulation program has to be applied for dimensioning the TAS (see 6.5).

Under the above-mentioned conditions, a cooling load calculation or a simulation for a convective system can be carried out for an entire 24 h period and with an internal temperature equal to the average room operative temperature during the occupancy hours. The results of this calculation to be taken into account as input for the present simplified model are the solar heat gains and the heat flows into the room from the external surface.

6.5 Dynamic building simulation programs

For all cases which are not in the range of validation of the simplified methods, TABS calculations have to be carried out by means of a detailed dynamic building-system model.

These TABS calculations have to take into account the water flow into the pipes, the heat conduction between upward and downward surface of the slab and the pipe level, heat conduction of each wall, mutual radiation between internal surfaces, convection with air, and the thermal balance of the air.

Whenever results of TABS calculations are reported, the computer program applied shall be specified.

7 Input for computer simulations of energy performance

To facilitate dynamic computer simulations of buildings with embedded radiant heating and cooling systems, the equivalent resistances between the heat conduction layer (pipe level) and the upward and downward surfaces can be used.

For type E, F, and G systems in ISO 11855-1, this resistance is directly calculated. Both the equivalent inward and outward resistance is calculated.

For type A, B, C and D systems (in ISO 11855-1 and EN 1264-2 and EN 1264-5) the equivalent resistance is calculated from the inward specific heat flow, q_i, and outward specific heat flow, q_u, taking into account the surface resistance according to this equation:

Equivalent resistance, $R = \Delta\theta/q - 1/h_t$ [m²·K/W]

where

$\Delta\theta$ is the heating/cooling medium temperature difference [K];

h_t is the total heat transfer coefficient (convection + radiation) between surface and space [W/(m²·K)].

Annex A
(informative)

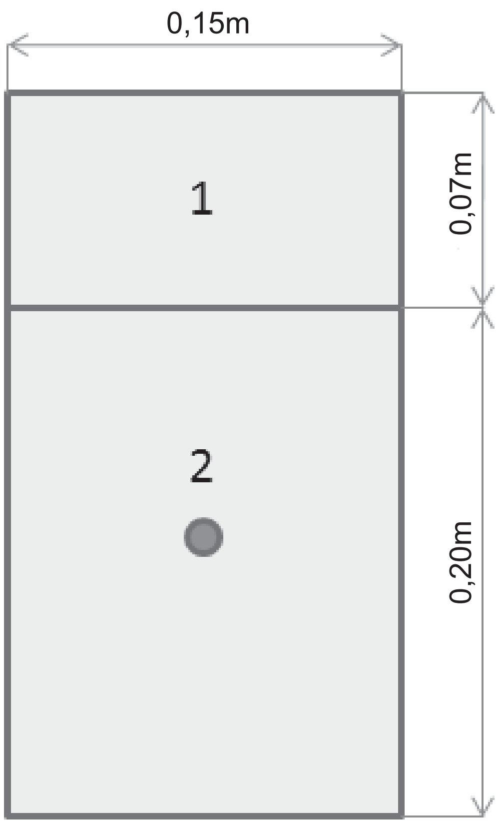
Simplified diagrams

Based on the simplified calculation method in 6.4, the following diagrams for design of a TABS have been developed. The diagram in Figure A.2 shows an example of the relation between internal heat gains, water supply temperature, heat transfer on the room side, hours of operation and heat transfer on the water side. The diagrams correspond to a concrete slab shown in Figure A.1 with a solid concrete floor, conductivity 1,2 W/(m·K), pipe spacing of 0,15 m and a permissible room temperature range of 21°C to 26°C.

The upper diagram in Figure A.2 shows on the Y-axis the maximum permissible total heat gain in space (internal gains plus solar gains) [W/m^2], and on the X-axis the required water supply temperature. The lines in the diagram correspond to different hours of operation (8 h, 12 h, and 24 h) and different daily energy gains [Wh/(m^2·d)].

The lower diagram in Figure A.2 shows the cooling power [W/m^2] required on the water side (to size the chiller) for TAS as a function of water supply temperature and operation time. Further, the amount of energy rejected per day is indicated [Wh/(m^2·d)].

The example shows that by a maximum internal heat gain of 48 W/m^2 and 8 h operation, a supply water temperature of 17,8 °C is required. If, instead, the system is in operation for 24 h, a supply water temperature of 21,3 °C is required. In total, the amount of energy rejected from the room is approximately. 460 Wh/m^2 per day. The required cooling power on the water side is for 8 h operation 58 W/m^2 and for 24 h operation only 20 W/m^2. Thus, for a 24 h operation, the chiller can be much smaller.

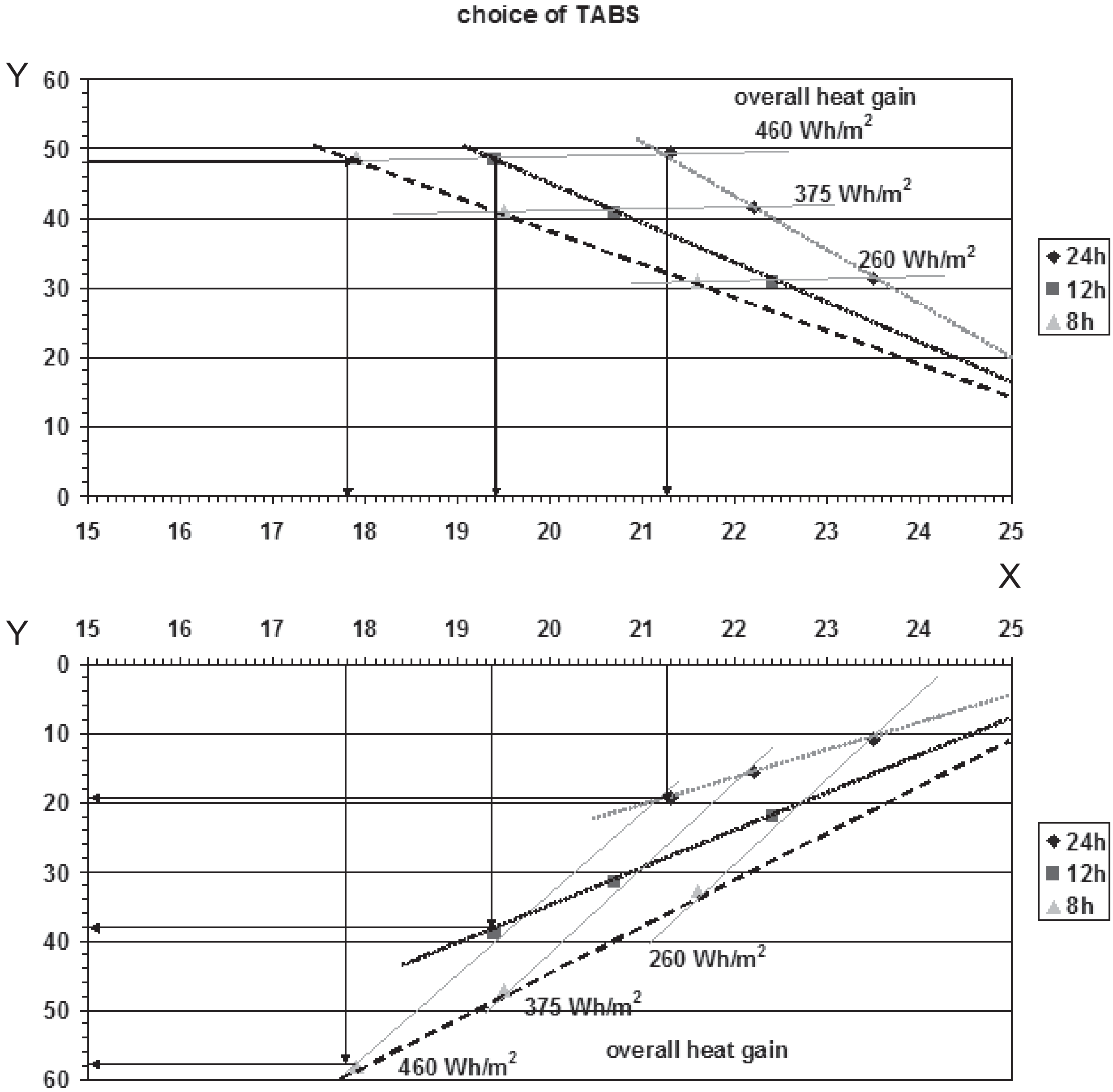


Key

1 concrete

2 reinforced concrete

Figure A.1 — Slab used in the simplified calculations



Key

X (upper diagram) supply water temperature, °C

Y (upper diagram) maximum heat gain, W/m^2

Y (lower diagram) size of the chiller, W/m^2

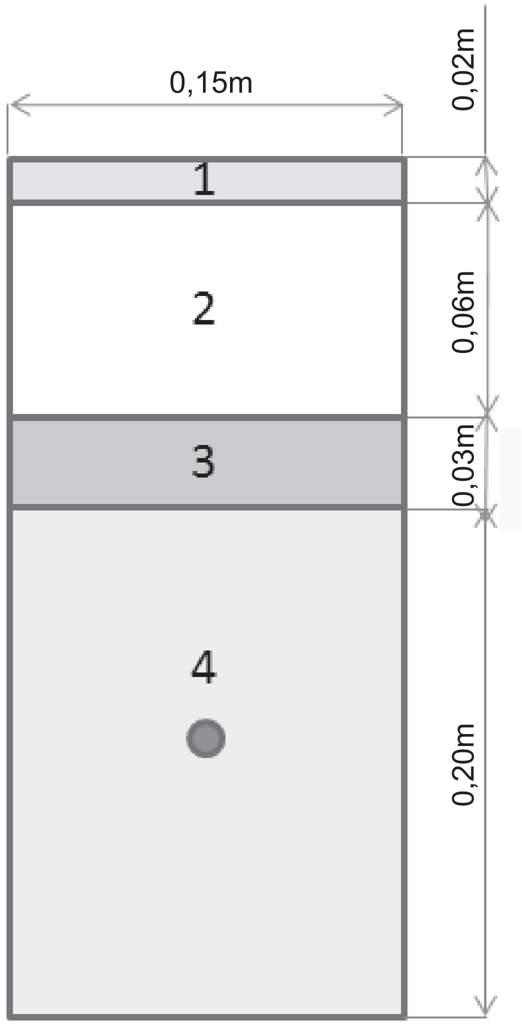
Figure A.2 — Simple diagrams showing the relation between heat gains in the room, lines for system running hours, supply water temperature θ_w, and energy removal on the water side

The diagrams in Figure A.4 correspond to a concrete slab shown in Figure A.3 with a solid concrete floor (conductivity 1,2 W/(m·K)), pipe spacing of 0,15 m and a permissible room temperature range of 21°C to 26°C.

The upper diagram in Figure A.4 shows on the Y-axis the maximum permissible total heat gain in space (internal gains plus solar gains) [W/m^2], and on the X-axis the required water supply temperature. The lines in the diagram correspond to different hours of operation (8 h, 12 h, and 24 h) and different daily energy gains [Wh/(m^2·d)].

The lower diagram in Figure A.4 shows the cooling power [W/m^2] required on the water side (to size the chiller) for TAS as a function of water supply temperature and operation time. Further, the amount of energy rejected per day is indicated [Wh/(m^2·d)].

The example shows that by a maximum internal heat gain of 48 W/m^2 and 8 h operation, a supply water temperature of 17,0 °C is required. If, instead, the system is in operation for 24 h, a supply water temperature of 20,5 °C is required. In total, the amount of energy rejected from the room is approximately 460 Wh/m^2 per day. The required cooling power on the water side is for an 8 h operation 58 W/m^2 and for a 24 h operation only 20 W/m^2. Thus, for a 24 h operation, the chiller can be much smaller.



Key

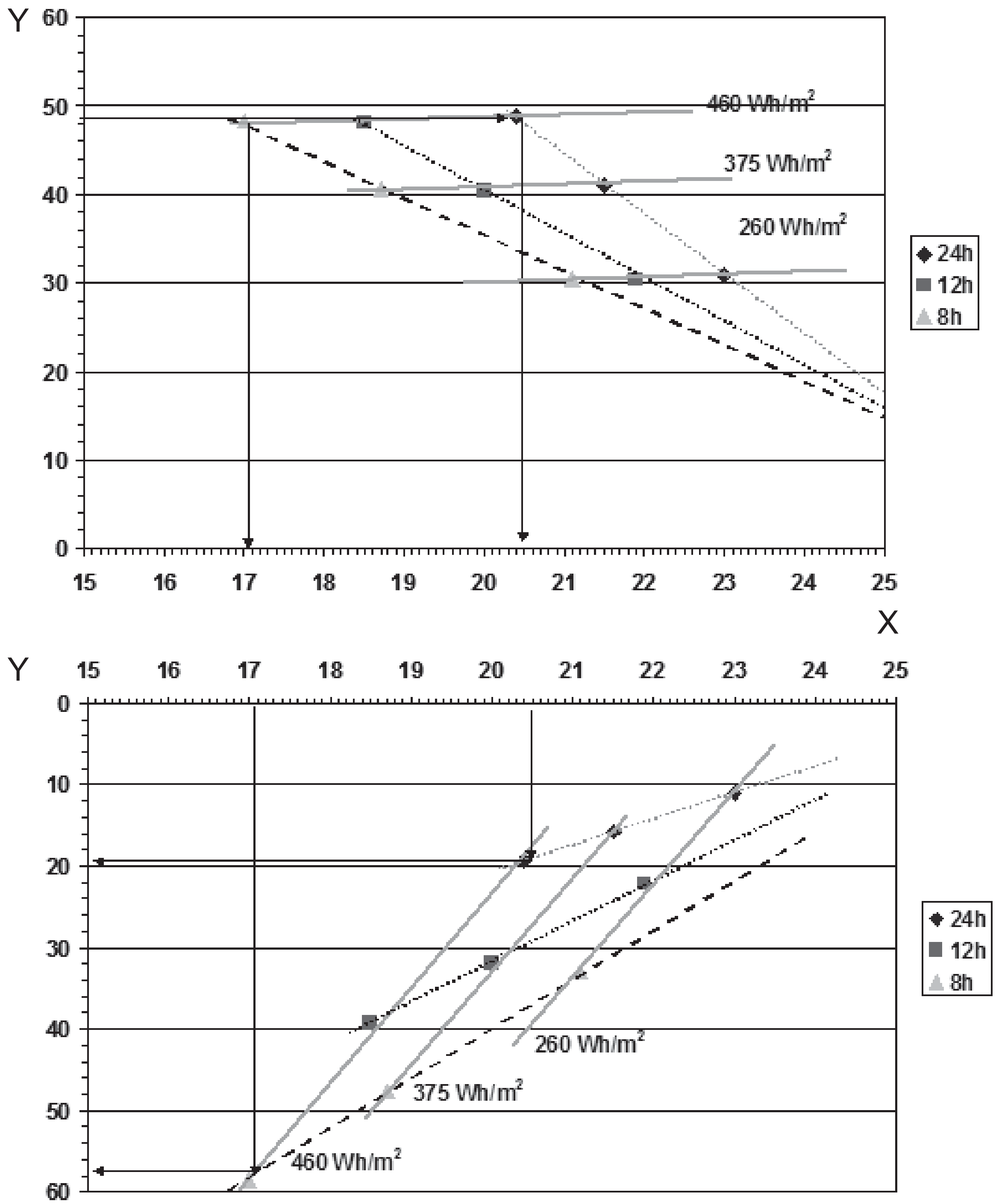
1 wood

2 concrete

3 fibreglass

4 reinforced concrete

Figure A.3 — Slab used in the simplified calculations



Key

X (upper diagram) °C

Y (upper diagram) Q_l, W/m^2

Y (lower diagram) Q_w, W/m^2

Figure A.4 — Simple diagrams showing the relation between heat gains in the room, lines for system running hours, supply water temperature θ_w, and energy removal on the water side

Diagrams like the ones in Figures A.2 and A.4 can be extended to different maximum operative temperatures allowed (but keeping the same room temperature drift). Such an extension can be performed by modifying the X-axis of both of the diagrams by the following equation:

$$\theta_{\text{Water,In}}^{\text{Setp}} = \theta_{\text{Water,In,Ref}}^{\text{Setp}} + \left(\theta_{\text{Comfort}}^{\text{Max}} - \theta_{\text{Comfort,Ref}}^{\text{Max}}\right) \quad [°\text{C}] \tag{A.1}$$

where

$\theta_{\text{Comfort}}^{\text{Max}}$ is the maximum allowable operative temperature in the case under consideration [°C];

$\theta_{\text{Comfort,Ref}}^{\text{Max}}$ is the maximum allowable operative temperature in the reference case of the diagram [°C];

$\theta_{\text{Water,In}}^{\text{Setp}}$ is the water inlet temperature in the case under consideration [°C];

$\theta_{\text{Water,In,Ref}}^{\text{Setp}}$ is the water inlet temperature in the reference case of the diagram [°C].

Moreover, the second diagrams in Figures A.2 and A.4 can be substituted by the following equation, if no graphical support is needed:

$$Q_{\text{w}} = \frac{E_{\text{Day}}}{n_{\text{h}}} \quad [\text{W/m}^2] \tag{A.2}$$

where

Q_{w} is the average specific cooling power of TABS [W/m^2];

E_{Day} is the specific daily energy gains [Wh/m^2];

n_{h} is the number of running hours [h].

As regards the heating capacity, dynamic calculations can also be carried out when looking at the possibility to use the system only for a part of the day. If steady state calculations are needed, this shall be done by using the Resistance Method introduced in ISO 11855-2.

Annex B
(normative)

Calculation method

B.1 Pipe level

R_t is the total thermal resistance [(m^2·K)/W] between the water supply temperature and the pipe level temperature, determined by the Resistance Method (for further details see ISO 11855-2). R_t can be calculated through Equation (B.1):

$$R_t = R_z + R_w + R_r + R_x \tag{B.1}$$

where

$$R_z = \frac{1}{2 \cdot \dot{m}_{H,sp} \cdot c_w}, \quad R_w = \frac{T^{0,13}}{8 \cdot \pi}\left(\frac{d_a - 2 \cdot s_R}{\dot{m}_{H,sp} \cdot L_R}\right)^{0,87}, \quad R_p = \frac{T \cdot \ln\left(\frac{d_a}{d_a - 2 \cdot s_R}\right)}{2 \cdot \pi \cdot \lambda_r}, \text{ and } \quad R_x = \frac{T \cdot \ln\left(\frac{T}{\pi \cdot d_a}\right)}{2 \cdot \pi \cdot \lambda_b}$$

Two conditions shall be fulfilled for the application of these equations:

— the equation for R_x is valid only if s_1 /W > 0,3, s_2 /W > 0,3, and da/W < 0,2;

— the equation for R_z is valid only if $\dot{m}_{H,sp} \cdot c_w \cdot (R_w + R_p + R_x) \geq \frac{1}{2}$.

If both conditions are fulfilled, the equation $R_t = R_z + R_w + R_p + R_x$ can be applied.

B.2 Thermal nodes composing the slab and room

The slab is composed of $J = J_1 + J_2$ material layers, where J_1 is the number of layers constituting the upper part of the slab and J_2 is the number of layers constituting the lower one. As a consequence, J sets of physical properties (ρ_j, c_j, λ_j) shall be known. Besides, each layer has its own thickness, δ_j, thus, for geometrical consistency:

$$s_1 = \sum_{j=1}^{J_1} \delta_j \quad \text{and} \quad s_2 = \sum_{j=J_1+1}^{J_1+J_2} \delta_j$$

For the calculations, each material layer is subdivided into a number of smaller divisions. For each material layer, the number of layers, m_j, into which it is divided for the calculations, shall be decided. Each division inherits the physical properties from the material layer which it belongs to. Each layer division constitutes a thermal node, that is a finite volume where a local heat balance is performed, in order to get temperatures and heat flows taking place within the slab and the room.

For a consistent description of the thermal behaviour of the slab and room, more thermal nodes shall be defined. Totally, the following thermal nodes shall be built up:

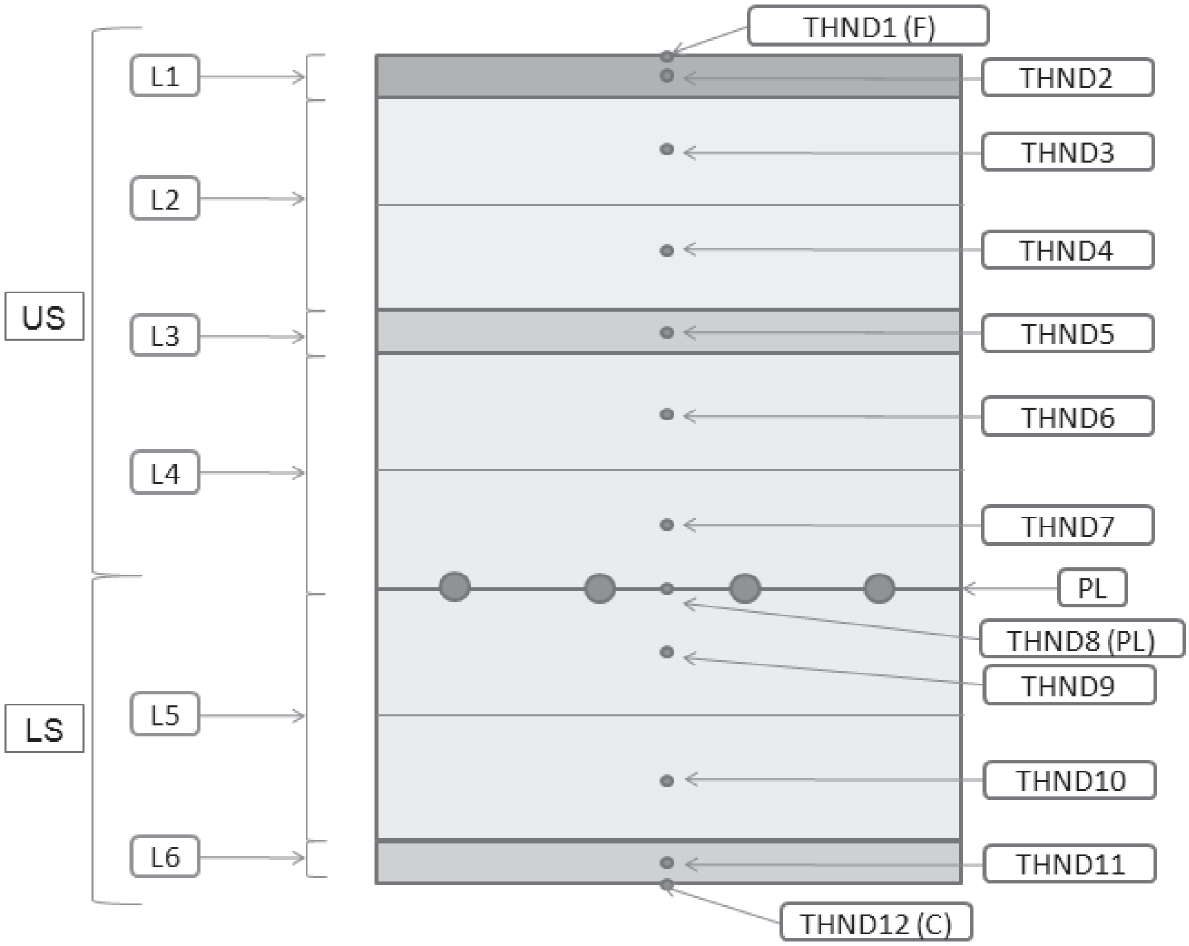
— Thermal nodes representing the slab divisions (thermal nodes "I", standing for "internal");

- Thermal node placed at the floor surface, over additional thermal resistances such as carpets, moquette, and raised floor (thermal node "F", standing for "floor");
- Thermal node placed at the pipe level surface, connecting the slab with the water circuit (thermal node "PL", standing for "pipe level");
- Thermal node placed at the ceiling surface, below additional thermal resistances such as suspended ceiling (thermal node "C", standing for "ceiling");
- Thermal node placed at the surface of the internal walls, over the thermal resistance constituted by the internal covering, such as the plaster layer (thermal node "IWS", standing for "internal wall surface");
- Thermal node placed inside the internal walls (thermal node "IW", standing for "internal walls");
- Thermal node representing the air node (thermal node "A", standing for "air").

The thermal nodes should be enumerated according to the following the following rules:

- Thermal node 1: thermal node "F";
- Thermal nodes 2 to $1+\sum_{1}^{J_1} m_j$: thermal nodes "I" representing the upper part of the slab;
- Thermal node $2+\sum_{1}^{J_1} m_j$: thermal node "PL";
- Thermal nodes $3+\sum_{1}^{J_1} m_j$ to $2+\sum_{1}^{J_1+J_2} m_j$: thermal nodes "I" representing the lower part of the slab;
- Thermal node $3+\sum_{1}^{J_1+J_2} m_j$: thermal node "C";
- Thermal node $4+\sum_{1}^{J_1+J_2} m_j$: thermal node "IWS";
- Thermal node $5+\sum_{1}^{J_1+J_2} m_j$: thermal node "IW";
- Thermal node $6+\sum_{1}^{J_1+J_2} m_j$: thermal node "A".

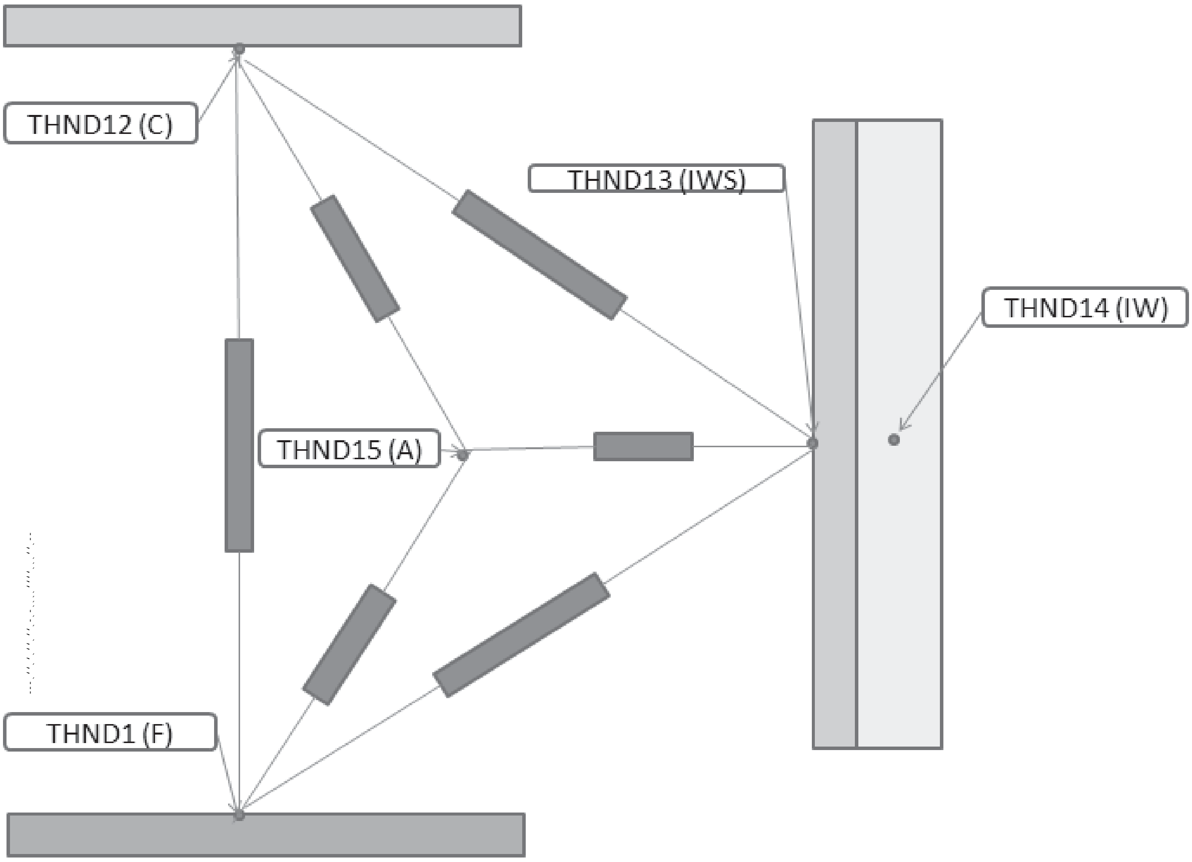
The following figures summarize the thermal nodes mentioned above.



Key

C	ceiling
F	floor
L	layer
LS	lower part of the slab
PL	pipe level
THND	thermal node
US	upper part of the slab

Figure B.1 — Example of thermal nodes representing the slab



Key

A	air
C	ceiling
CHT	convective heat transfer
F	floor
IW	internal walls
IWS	internal wall surface
RHT	radiant heat transfer
THND	thermal node

Figure B.2 — Example of thermal nodes representing the room and correlated heat transfer connections

In order to perform heat transfer calculations, each thermal node is characterized by three main physical magnitudes:

— thermal inertia of the p-th thermal node:

For thermal nodes “I”: $C_p = \rho_j \cdot c_j \cdot \dfrac{\delta_j}{m_j}$ (B.2a)

For thermal nodes “IW”: $C_p = C_W$ (B.2b)

For thermal nodes “F”, “PL”, “C”, “IWS”, and “A”: $C_p = 0$ (B.2c)

— thermal resistance RU_p, which connects the p-th thermal node with the boundary of the previous thermal node:

For thermal nodes “I”: $RU_p = \frac{\delta_j}{2 \cdot m_j \cdot \lambda_j}$ (B.3a)

For thermal nodes “C”: $RU_p = R_{Add\ C}$ (B.3b)

For thermal nodes “IW”: $RU_p = R_{Walls}$ (B.3c)

For thermal nodes “F”, “PL”, “IWS”, and “A”: $RU_p = 0$ (B.3d)

— thermal resistance RL_p, which connects the p-th thermal node with the boundary of the next thermal node;

For thermal nodes “I”: $RL_p = \frac{\delta_j}{2 \cdot m_j \cdot \lambda_j}$ (B.4a)

For thermal nodes “F”: $RL_p = R_{Add\ F}$ (B.4b)

For thermal nodes “IWS”: $RL_p = R_{Walls}$ (B.4c)

For thermal nodes “PL”, “C”, “IW”, and “A”: $RL_p = 0$ (B.4d)

B.3 Calculations for the generic h-th hour

Further data required to perform the simulations are listed below:

— A_F : Area of the heating/cooling surface [m^2]

— A_W : Total area of the internal vertical walls [m^2]

— $F_{vF\text{-}C}$: view factor between the floor and the ceiling [-]

— $F_{vF\text{-}EW}$: view factor between the floor and the external walls [-]

— $h_{A\text{-}F}$: convective heat transfer coefficient between the air and the floor [W/(m^2·K)]

— $h_{A\text{-}C}$: convective heat transfer coefficient between the air and the ceiling [W/(m^2·K)]

— $h_{A\text{-}W}$: convective heat transfer coefficient between the air and the internal walls [W/(m^2·K)]

— R_{AddC} : additional thermal resistance covering the lower side of the slab [(m^2·K)/W]

— R_{AddF} : additional thermal resistance covering the upper side of the slab [(m^2·K)/W]

— R_{Walls} : wall surface thermal resistance [(m^2·K)/W]

— C_W : average specific thermal capacity of the internal vertical walls [m^2]

— R_t : circuit total thermal resistance [(m^2·K)/W]

— $\dot{m}_{H,sp}$: specific design water flow in the circuit [kg/(s·m^2)]

- c_{W} : specific heat of water [J/(kg·K)]
- $f_{\mathrm{rm}}^{\mathrm{h}}$: running mode for each h-th hour [-]
- $P_{\mathrm{Circuit}}^{\mathrm{Max,h}}$: maximum cooling power reserved to the circuit under examination for each h-th hour [W]
- $\theta_{\mathrm{Water,In}}^{\mathrm{Setp,h}}$: water inlet set-point temperature for each h-th hour [°C]
- $Q_{\mathrm{IntConv}}^{\mathrm{h}}$: internal convective heat gains for each h-th hour [W]
- $Q_{\mathrm{IntRad}}^{\mathrm{h}}$: internal radiant heat gains for each h-th hour [W]
- $Q_{\mathrm{PrimAir}}^{\mathrm{h}}$: primary air convective heat gains for each h-th hour [W]
- $Q_{\mathrm{Sun}}^{\mathrm{h}}$: solar heat gains in the room for each h-th hour [W]
- $Q_{\mathrm{Transm}}^{\mathrm{h}}$: transmission heat gains for each h-th hour [W]
- Δt : calculation time step [s]. For hourly time steps: Δt = 3 600 s
- n^{Max} : maximum number of iterations allowed [-]
- ξ^{Max} : maximum tolerance allowed [K]

The values of $Q_{\mathrm{IntConv}}^{\mathrm{h}}$, $Q_{\mathrm{IntRad}}^{\mathrm{h}}$, $Q_{\mathrm{PrimAir}}^{\mathrm{h}}$, $Q_{\mathrm{Sun}}^{\mathrm{h}}$, and $Q_{\mathrm{Transm}}^{\mathrm{h}}$ shall be known for the whole day. $Q_{\mathrm{IntConv}}^{\mathrm{h}}$, $Q_{\mathrm{IntRad}}^{\mathrm{h}}$ and $Q_{\mathrm{PrimAir}}^{\mathrm{h}}$ depend on the people and the equipment in the room and on the possible air supply and infiltration, and can thus be estimated. $Q_{\mathrm{Sun}}^{\mathrm{h}}$ and $Q_{\mathrm{Transm}}^{\mathrm{h}}$ can be calculated by other software (through commercial software enabling calculation of the cooling loads of a room with a constant room temperature equal to the average room operative temperature during occupancy hours).

For every time step, the running strategy of the circuit $f_{\mathrm{rm}}^{\mathrm{h}}$ shall be decided before the simulation is started, and the supply water temperature $\theta_{\mathrm{Water,Inlet}}^{\mathrm{Setp,h}}$ is an input as well. These parameters are chosen by the designer and, by performing the simulation with different sets of parameters, it is possible to approach the best combination of running strategy of the circuit and supply water temperature.

The following shortcuts are useful in the following calculations:

$$F_{\mathrm{vF-W}} = 1 - \cdot F_{\mathrm{vF-EW}} - F_{\mathrm{vF-C}} \qquad [-]$$

$$h_{\mathrm{F-W}} = 5{,}5 \cdot F_{\mathrm{vF-W}} \qquad [\mathrm{W/(m^2 \cdot K)}]$$

$$h_{\mathrm{F-C}} = 5{,}5 \cdot F_{\mathrm{vF-C}} \qquad [\mathrm{W/(m^2 \cdot K)}]$$

At each h-th hour, the following calculations shall be executed:

- Calculation of the heat loads acting in the room:

$$Q_{\mathrm{Conv}}^{\mathrm{h}} = 0{,}15 \cdot Q_{\mathrm{Transm}}^{\mathrm{h}} + Q_{\mathrm{IntConv}}^{\mathrm{h}} + Q_{\mathrm{PrimAir}}^{\mathrm{h}} \qquad [\mathrm{W}]$$

$$Q_{\mathrm{Rad}}^{\mathrm{n}} = 0{,}85 \cdot Q_{\mathrm{Transm}}^{\mathrm{h}} + Q_{\mathrm{IntRad}}^{\mathrm{h}} + Q_{\mathrm{Sun}}^{\mathrm{h}} \qquad [\mathrm{W}]$$

From estimations performed on several detailed simulations, it was assumed that about 15 % of the heat gains passing through the external wall act on the room in a convective way, while the remaining 85 % can be considered a pure radiant heat load.

From this point on, iterations shall be performed, at each hour, in order to approach the solution of the thermal field in the room. The main points of the iterations are listed below:

— Determination of the water supply temperature. The inlet water temperature is calculated by taking into account the average heat flow extracted in the hour under consideration, according to the following equation:

$$\theta_{\mathrm{Water,In}}^{\mathrm{h}} = \max\left(\theta_{\mathrm{Water,in}}^{\mathrm{Setp,h}}, \theta_{\mathrm{Water,in}}^{\mathrm{h}} + \frac{\left(Q_{\mathrm{Circuit}}^{\mathrm{h}} - P_{\mathrm{Circuit}}^{\mathrm{Max,h}}\right)}{\dot{m}_{\mathrm{H,sp}}^{\mathrm{h}} \cdot A_{\mathrm{F}} \cdot c_{\mathrm{w}}}\right) \text{ [°C]}$$

where

$\theta_{\mathrm{Water,In}}^{\mathrm{Setp,h}}$ is the water inlet set-point temperature in the h-th hour [°C];

$\theta_{\mathrm{Water,In}}^{\mathrm{h}}$ is the water inlet actual temperature in the h-th hour [°C];

$Q_{\mathrm{Circuit}}^{\mathrm{h}}$ is the heat flow extracted by the circuit in the h-th hour [W];

$P_{\mathrm{Circuit}}^{\mathrm{Max,h}}$ is the maximum cooling power reserved to the circuit under consideration in the h-th hour [W];

$\dot{m}_{\mathrm{H,sp}}^{\mathrm{h}}$ is the specific water mass flow in the circuit in the h-th hour [kg/(s·m^2)];

A_{F} is the area of the heating/cooling surface [m^2];

c_{w} is the specific heat of the fluid flowing in the circuit [J/(kg·K)].

— Calculation of the temperature of each thermal node, at the current iteration of the h-th hour.

Each p-th thermal node has peculiar characteristics that can be summarized in coefficients (“H”), to be used as shortcuts in the calculation of the energy balance for each thermal node:

H_{A} is the coefficient summarizing the heat transfer coefficient between the p-th thermal node and thermal node “air” [W/K];

H_{IWS} is the coefficient summarizing the heat transfer coefficient between the p-th thermal node and thermal node “internal wall surface” [W/K];

H_{F} is the coefficient summarizing the heat transfer coefficient between the p-th thermal node and thermal node “floor” [W/K];

H_{C} is the coefficient summarizing the heat transfer coefficient between the p-th thermal node and thermal node “ceiling” [W/K];

H_{Rad} is the fraction of room radiant heat loads impinging on the p-th thermal node [-];

H_{Conv} is the fraction of room convective heat loads acting on the p-th thermal node [-];

H_{CondUp} is the coefficient summarizing the thermal conduction connection between the p-th thermal node and the previous thermal node [i.e. the (p-1)-th thermal node] [W/K];

H_{CondDown} is the coefficient summarizing the thermal conduction connection between the p-th thermal node and the next thermal node (i.e. the (p+1)-th thermal node) [W/K];

$H_{Inertia}$ is the coefficient summarizing the inertia contribution at the p-th thermal node [W/K];

$H_{Circuit}$ is the coefficient summarizing the heat transfer coefficient between the p-th thermal node and the water inlet temperature [W/K].

The coefficients seen above are specified for each thermal node, in Table B.1.

Table B.1 — Coefficients for the calculation of the temperature at each thermal node

	p-th Node = Node “F”	p-th Node = Node “I”	p-th Node = Node “PL”	p-th Node = Node “C”	p-th Node = Node “IWS”	p-th Node = Node “IW”	p-th Node = Node “A”
H_{A}	$h_{A-F} \cdot A_{F}$	0.	0.	$h_{A-C} \cdot A_{F}$	$h_{A-W} \cdot A_{W}$	0.	0.
H_{IWS}	$h_{F\text{-}W} \cdot A_{F}$	0.	0.	$h_{F\text{-}W} \cdot A_{F}$	0.	0.	$h_{A-W} \cdot A_{W}$
H_{F}	0.	0.	0.	$h_{F\text{-}C} \cdot A_{F}$	$h_{F\text{-}W} \cdot A_{F}$	0.	$h_{A-F} \cdot A_{F}$
H_{C}	$h_{F\text{-}C} \cdot A_{F}$	0.	0.	0.	$h_{F\text{-}W} \cdot A_{F}$	0.	$h_{A-C} \cdot A_{F}$
H_{Rad}	$\frac{A_{F}}{2 \cdot A_{F} + A_{W}}$	0.	0.	$\frac{A_{F}}{2 \cdot A_{F} + A_{W}}$	$\frac{A_{W}}{2 \cdot A_{F} + A_{W}}$	0.	0.
H_{Conv}	0.	0.	0.	0.	0.	0.	1.
H_{CondUp}	0.	$\frac{1}{RU_{p} + RD_{p-1}} \cdot A_{F}$	$\frac{1}{RU_{p} + RD_{p-1}} \cdot A_{F}$	$\frac{1}{RU_{p} + RD_{p-1}} \cdot A_{F}$	0.	$\frac{1}{RU_{p} + RD_{p-1}} \cdot A_{W}$	0.
$H_{CondDown}$	$\frac{1}{RD_{p} + RU_{p+1}} \cdot A_{F}$	$\frac{1}{RD_{p} + RU_{p+1}} \cdot A_{F}$	$\frac{1}{RD_{p} + RU_{p+1}} \cdot A_{F}$	0.	$\frac{1}{RD_{p} + RU_{p+1}} \cdot A_{W}$	0.	0.
$H_{Inertia}$	0.	$\frac{C_{p} \cdot A_{F}}{\Delta t}$	0.	0.	0.	$\frac{C_{p} \cdot A_{W}}{\Delta t}$	0.
$H_{Circuit}$	0.	0.	$\frac{1}{R_{t}} \cdot A_{F}$	0.	0.	0.	0.

By means of the coefficients seen above it is possible to calculate the temperature of each node at the end of the time step under consideration. At each iteration, the temperature of each thermal node, at the end of the time step under consideration, is calculated via the following equation:

$$\theta_{p}^{h}=\frac{\left(\begin{array}{l}H_{Air}\cdot\theta_{A}^{h}+H_{IWS}\cdot\theta_{IWS}^{h}+H_{F}\cdot\theta_{F}^{h}+H_{C}\cdot\theta_{C}^{h}+H_{Rad}\cdot Q_{Rad}^{h}+H_{Conv}\cdot Q_{Conv}^{h}+\\+H_{CondUp}\cdot\theta_{p-1}^{h}+H_{CondDown}\cdot\theta_{p+1}^{h}+H_{Inertia}\cdot\theta_{p}^{h-1}+H_{Circuit}\cdot\theta_{Water,In}^{h}\cdot f_{rm}^{h}\end{array}\right)}{H_{A}+H_{IWS}+H_{F}+H_{C}+H_{CondUp}+H_{CondDown}+H_{Inertia}+H_{Circuit}\cdot f_{rm}^{h}}\ [°C]$$

The achieved temperatures θ_{p}^{h} are stored and compared with the ones calculated at the previous iteration ($\theta_{p}^{h'}$), in the following way:

— Calculation of the actual tolerance at the current iteration: $\xi=\sum_{p}\left(\theta_{p}^{h}-\theta_{p}^{h'}\right)$ [K];

— Comparison of the actual tolerance with the maximum tolerance allowed: $\xi<\xi_{Max}$.

If $\xi>\xi_{Max}$ and $n<n_{Max}$, then the required accuracy has not been reached and another iteration must be executed.

If one more iteration more must be executed, then $Q_{Circuit}^{h}$ is calculated via the following equation:

$$Q_{Circuit}^{h}=\frac{\left(\theta_{PL}^{h}-\theta_{Water,In}^{h}\right)}{R_{t}}\cdot f_{rm}^{h}\cdot A_{F}\quad [W].$$

Otherwise, the following quantities can be calculated and stored:

$$Q_{Circuit}^{h}=\frac{\left(\theta_{PL}^{h}-\theta_{Water,In}^{h}\right)}{R_{t}}\cdot f_{rm}^{h}\cdot A_{F}\quad [W]$$

$$Q_{F}^{h}=h_{A-F}\cdot A_{F}\left(\theta_{A}^{h}-\theta_{F}^{h}\right)+h_{F-C}\cdot A_{F}\left(\theta_{C}^{h}-\theta_{F}^{h}\right)+h_{F-W}\cdot A_{F}\left(\theta_{IWS}^{h}-\theta_{F}^{h}\right)+\frac{A_{F}}{2\cdot A_{F}+A_{W}}\cdot Q_{Rad}^{h}\quad [W]$$

$$Q_{C}^{h}=h_{A-C}\cdot A_{F}\left(\theta_{A}^{h}-\theta_{C}^{h}\right)+h_{F-C}\cdot A_{F}\left(\theta_{F}^{h}-\theta_{C}^{h}\right)+h_{F-W}\cdot A_{F}\left(\theta_{IWS}^{h}-\theta_{C}^{h}\right)+\frac{A_{F}}{2\cdot A_{F}+A_{W}}\cdot Q_{Rad}^{h}\quad [W]$$

$$Q_{IWS}^{h}=h_{A-W}\cdot A_{W}\left(\theta_{A}^{h}-\theta_{IWS}^{h}\right)+h_{F-W}\cdot A_{F}\left(\theta_{F}^{h}-\theta_{IWS}^{h}\right)+h_{F-W}\cdot A_{F}\left(\theta_{C}^{h}-\theta_{IWS}^{h}\right)+ +\frac{A_{W}}{2\cdot A_{F}+A_{W}}\cdot Q_{Rad}^{h}\quad [W]$$

$$\theta_{MR}^{h}=\frac{A_{F}\cdot\theta_{F}^{h}+A_{F}\cdot\theta_{C}^{h}+A_{W}\cdot\theta_{IWS}^{h}}{2\cdot A_{F}+A_{W}}\quad [°C]$$

$$\theta_{Op}^{h}=\frac{\theta_{A}^{h}+\theta_{MR}^{h}}{2}\quad [°C]$$

$$\theta^{h}_{Water,Out} = \theta^{h}_{Water,In} + \frac{Q^{h}_{Circuit}}{\dot{m}_{H,sp} \cdot A_F \cdot c_w} \quad [°C]$$

B.4 Sizing of the system

The allowed range for the operative temperature of the room is usually 20 °C to 26 °C. If the room operative temperature is always in this range (or in any range of comfort temperatures chosen by the planner and agreeing with local or international standards), then the system is well sized. Otherwise the running strategy, the supply water temperature or the circuit characteristics have to be changed.

Annex C
(informative)

Tutorial guide for assessing the model

The following values will be used:

Main slab input data	J_1	3	Input
	J_2	1	Input
	δ_1	0,02 m	Input
	m_1	2	Input
	λ_1	0,17 W/(m·K)	Input
	ρ_1	700 kg/m^3	Input
	c_1	2300 J/(kg·K)	Input
	δ_2	0,07 m	Input
	m_2	3	Input
	λ_2	1,1 W/(m·K)	Input
	ρ_2	1900 kg/m^3	Input
	c_2	850 J/(kg·K)	Input
	δ_3	0,1 m	Input
	m_3	4	Input
	λ_3	1,9 W/(m·K)	Input
	ρ_3	2000 kg/m^3	Input
	c_3	880 J/(kg·K)	Input
	δ_4	0,1 m	Input
	m_4	4	Input
	λ_4	1,9 W/(m·K)	Input
	ρ_4	2000 kg/m^3	Input
	c_4	880 J/(kg·K)	Input
Δt		3600 s	Input
Main room input data	A_F	30 m^2	Input
	A_W	48 m^2	Input
	h_{A-F}	1,5 W/(m^2·K)	Input
	h_{A-C}	5,5 W/(m^2·K)	Input
	h_{A-W}	2,5 W/(m^2·K)	Input
	$F_{v\ F-EW}$	0,21	Input
	$F_{v\ F-C}$	0,35	Input
	R_{addF}	0,1 (m^2·K)/W	Input
	R_{addC}	0 (m^2·K)/W	Input
	R_{Walls}	0,05 (m^2·K)/W	Input
	C_W	25600 J/(m^2·K)	Input
Main circuit input data	R_t	0,073 (m^2·K)/W	Input
	c_w	4187 J/(kg·K)	Input
	$\dot{m}_{H,sp}$	0,01 kg/(m^2·s)	Input

Hourly boundary conditions			
From 00:00 to 8:00	Q^{h}_{Conv}	30 W	Input
	Q^{h}_{Rad}	10 W	Input
	f^{h}_{rm}	1	Input
	$\theta^{Setp,h}_{Water,In}$	20,0°C	Input
	$P^{Max,h}_{Circuit}$	1000 W	Input
From 8:00 to 19:00	Q^{h}_{Conv}	400 W	Input
	Q^{h}_{Rad}	300 W	Input
	f^{h}_{rm}	0	Input
	$\theta^{Setp,h}_{Water,In}$	20,0°C	Input
	$P^{Max,h}_{Circuit}$	0 W	Input
From 19:00 to 24:00	Q^{h}_{Conv}	150 W	Input
	Q^{h}_{Rad}	100 W	Input
	f^{h}_{rm}	1	Input
	$\theta^{Setp,h}_{Water,In}$	20,0°C	Input
	$P^{Max,h}_{Circuit}$	0 W	Input

Main results

Time	θ^{h}_{F} [°C]	θ^{h}_{C} [°C]	θ^{h}_{A} [°C]	Q^{h}_{F} [W]	Q^{h}_{C} [W]	Q^{h}_{IWS} [W]	$Q^{h}_{lCircuit}$ [W]
1	22,7	22,3	22,7	-1	109	-68	770
2	22,5	22,1	22,4	-8	94	-46	716
3	22,3	22,0	22,2	-11	85	-34	666
4	22,2	21,8	22,1	-12	79	-27	620
5	22,0	21,7	21,9	-12	75	-23	577
6	21,9	21,6	21,8	-12	71	-20	537
7	21,8	21,5	21,7	-11	68	-18	501
8	21,6	21,4	21,6	-10	66	-16	467
9	22,5	21,8	23,4	124	442	134	0
10	22,7	22,1	23,8	147	472	81	0
11	22,9	22,3	24,1	161	485	54	0
12	23,1	22,5	24,3	170	490	39	0
13	23,3	22,7	24,5	176	492	32	0
14	23,5	22,9	24,7	179	493	28	0
15	23,6	23,1	24,9	181	493	26	0
16	23,8	23,3	25,0	182	493	25	0
17	24,0	23,4	25,2	183	493	24	0
18	24,1	23,6	25,4	184	493	24	0
19	24,3	23,8	25,5	184	492	23	0
20	23,8	23,5	24,3	89	246	-85	871
21	23,6	23,2	24,0	69	236	-55	915
22	23,4	23,0	23,8	55	234	-40	926
23	23,3	22,8	23,6	47	234	-32	878
24	23,1	22,6	23,4	42	234	-26	826

Annex D
(informative)

Computer program

```
PROGRAM TABS_CALC_ISOTC205_WG8

IMPLICIT NONE

TYPE lr ! Definition of layer
        INTEGER nDivisions ! Number of parts into which the layer must be divided in order to perform the calculations [-]
        REAL Thickness ! Thickness of the layer [m]
        REAL ThCond ! Conductivity of the material constituting the layer [W/(m K)]
        REAL Density ! Density of the material constituting the layer [Kg/m3]
        REAL SpecHeat ! Specific heat of the material constituting the layer [J/(kg K)]
END TYPE Lr

TYPE htldsandcrct ! Definition of the boundary conditions and results for heat loads, water temperature, running mode and maximum cooling power
        REAL RadHeatFlux ! Radiant heat flux imposed in the room in the current hour [W]
        REAL ConvHeatFlux ! Convective heat flux imposed in the room in the current hour [W]
        INTEGER RunningMode ! Hydronic circuit running mode in the current hour [1/0]
        REAL TWater_Setp ! Water setpoint inlet temperature in the current hour [°C]
        REAL MaxCoolingPower ! Maximum cooling power available for the circuit during the present hour [W]
        REAL MassFlow ! Mass flow in the circuit during the present hour [kg/s]
        REAL TAir ! Temperature of the air thermal node [°C]
        REAL TFloor ! Temperature of the floor thermal node [°C]
        REAL TPipeLevel ! Temperature of the pipe level thermal node [°C]
        REAL TCeiling ! Temperature of the ceiling thermal node [°C]
        REAL TWalls ! Temperature of the internal wall thermal node [°C]
        REAL TWater ! Temperature of the inlet water [°C]
        REAL QFloor ! Heat flow impinging on the floor surface [W]
        REAL QCeiling ! Heat flow impinging on the ceiling surface [W]
        REAL QWalls ! Heat flow impinging on the wall surface [W]
        REAL QCircuit ! Heat flow extracted by the water circuit [W]
ENDTYPE htldsandcrct

TYPE thrmlnd ! Definition thermal node
        REAL ThInertia ! Thermal capacity assigned to the present element [J/(K m2)]
        REAL RUp ! Resistance connecting the present element with the upper one [(m2 K)/W]
        REAL RDown ! Resistance connecting the present element with the lower one [(m2 K)/W]
        REAL PrevTemp ! Temperature of the thermal node during the previous hour [°C]
        REAL Temp ! Temperature of the thermal node during the current hour [°C]
        CHARACTER*1 Position ! Code for position of the thermal node
                ! ["F"(floor)/"I"(inside the slab)/"P"(pipe level)/"C"(ceiling)/"S"(surface of the walls)/"K"(core of the walls)/"A"(Air)]
        REAL Coeff_Air ! Support coefficient that takes into account the connection between the air thermal node ("A") and this thermal node [W/K]
        REAL Coeff_Wall ! Support coefficient that takes into account the connection between the wall thermal node ("S") and this thermal node [W/K]
        REAL Coeff_Floor ! Support coefficient that takes into account the connection between the floor thermal node ("F") and this thermal node [W/K]
        REAL Coeff_Ceiling ! Support coefficient that takes into account the connection between the ceiling thermal node ("C") and this thermal node [W/K]
        REAL Coeff_Rad ! Support coefficient that takes into account the connection between the radiation heat flux and this thermal node [-]
        REAL Coeff_Conv ! Support coefficient that takes into account the connection between the convection heat flux and this thermal node [-]
        REAL Coeff_CondUp ! Support coefficient that takes into account the connection between the upper thermal node and this thermal node [W/K]
        REAL Coeff_CondDown ! Support coefficient that takes into account the connection between the lower thermal node and this thermal node [W/K]
        REAL Coeff_Inertia ! Support coefficient that takes into account the inertia contribution for this thermal node [W/K]
        REAL Coeff_Circuit ! Support coefficient that takes into account the connection between the inlet water temperature and this thermal node [W/K]
ENDTYPE thrmlnd
```

```
INTEGER nLayersUp ! Number of layers constituting the upper part of the slab
INTEGER nLayersDown ! Number of layers constituting the lower part of the slab
TYPE (lr):: Layer(1:20) ! Maximum number of layers constituting the slab = 30
REAL FloorArea ! Area of the floor [m2]
REAL WallArea ! Area of the internal walls [m2]
REAL hAirToFloor ! Convective coefficient between the air and the floor [W/(m2 K)]
REAL hAirToCeiling ! Convective coefficient between the air and the ceiling [W/(m2 K)]
REAL hAirToWalls ! Convective coefficient between the air and the walls [W/(m2 K)]
REAL FvFloorToCeiling ! View factor between the floor and the ceiling [-]
REAL FvSlabToExtWall ! View factor between the floor and the external wall [-]
REAL FloorResistance ! Additional resistance on the floor (such as carpets or moquette) [(m2 K)/W]
REAL CeilingResistance ! Additional resistance covering the ceiling (such as suspended ceiling) [(m2 K)/W]
REAL WallResistance ! Resistance related to the thermal node of internal walls [(m2 K)/W]
REAL CWalls ! Specific thermal inertia of internal walls [J/(m2 K)]
REAL Rtot ! Resistance concerning the circuit and connecting the average pipe level temperature with the inlet water temperature [(m2 K)/W]
INTEGER TimeStep ! Calculation time step [s] Assumed: 3600 s
REAL FluidSpecHeat ! Specific heat of the fluid in the circuit [J/(kg K)]
INTEGER nHour ! Counter for hours (support variable) [-]
TYPE (htldsandcrct):: Boundary(1:24) ! Number of hours = 24
TYPE (thrmlnd):: ThNode(1:100) ! Maximum number of thermal nodes = 100
REAL hFloorToCeiling ! Radiant coefficient between the floor and the ceiling [W/(m2 K)]
REAL hSlabToWalls ! Radiant coefficient between the floor and the internal walls [W/(m2 K)]
REAL nThNodes ! Total number of thermal nodes (support variable) [-]
INTEGER nLayer ! Counter for layers (support variable) [-]
INTEGER nDivision ! Counter for divisions in layers (support variable) [-]
INTEGER nThNode_PipeLevel ! Ordinal number of the thermal node where the pipe level is [-]
REAL TolDailyMax ! Tolerance defining the reached convergence in daily calculation (support variable) [°C]
INTEGER nItDailyMax ! Maximum number of iterations allowed in reaching the convergence in daily calculation (support variable) [-]
REAL TolHourlyMax ! Tolerance defining the reached convergence in hourly calculation (support variable) [°C]
INTEGER nItHourlyMax ! Maximum number of iterations allowed in reaching the convergence in hourly calculation (support variable) [-]
REAL TolDaily ! Tolerance defining the status of convergence in daily calculation (support variable) [°C]
INTEGER nItDaily ! Number of iteration to reach the convergence in daily calculation (support variable) [-]
REAL TolHourly ! Tolerance defining the status of convergence in hourly calculation (support variable) [°C]
INTEGER nItHourly ! Number of iteration to reach the convergence in hourly calculation (support variable) [-]
REAL QCircuit ! Heat flow extracted by the water circuit (support variable) [W]
REAL TAir ! Temperature of the air thermal node (support variable) [°C]
REAL TFloor ! Temperature of the floor thermal node (support variable) [°C]
REAL TPipeLevel ! Temperature of the pipe level thermal node (support variable) [°C]
REAL TCeiling ! Temperature of the ceiling thermal node (support variable) [°C]
REAL TWalls ! Temperature of the internal wall thermal node (support variable) [°C]
REAL TWater ! Temperature of the inlet water (support variable) [°C]
REAL SumOfTemps ! Sum of temperatures of the thermal nodes during the whole day (support variable) [°C]
INTEGER nThNode ! Counter for thermal nodes (support variable) [-]
REAL SumOfTemps_Prev ! Sum of temperatures of the thermal nodes during the whole previous day (support variable) [°C]
REAL A ! Coefficient used to calculate the temperature of the thermal nodes (support variable) [°C]
REAL B ! Coefficient used to calculate the temperature of the thermal nodes (support variable) [°C]
REAL SuppTemp ! VAlue used to calculate the temperature of the thermal nodes (support variable) [°C]

REAL SumOfConv
REAL SumOfRad
REAL SumOfQFloor
REAL SumOfQCeiling
REAL SumOfQWalls
REAL SumOfQCircuit

    ! Input data -->

    nLayersUp = 3
    Layer(1).nDivisions = 2 ! Layer(1)
    Layer(1).Thickness = 0.02
```

```
Layer(1).ThCond = 0.17
Layer(1).SpecHeat = 2300.
Layer(1).Density = 700.
Layer(2).nDivisions = 3 ! Layer(2)
Layer(2).Thickness = 0.07
Layer(2).ThCond = 1.1
Layer(2).SpecHeat = 850.
Layer(2).Density = 1900.
Layer(3).nDivisions = 4 ! Layer(3)
Layer(3).Thickness = 0.1
Layer(3).ThCond = 1.9
Layer(3).SpecHeat = 880.
Layer(3).Density = 2000.

nLayersDown = 1
Layer(4).nDivisions = 4 ! Layer(4)
Layer(4).Thickness = 0.1
Layer(4).ThCond = 1.9
Layer(4).SpecHeat = 880.
Layer(4).Density = 2000.

FloorArea = 30
WallArea = 48

hAirToFloor = 1.5
hAirToCeiling = 5.5
hAirToWalls = 2.5

FvFloorToCeiling = 0.21
FvSlabToExtWall = 0.35

FloorResistance = 0.10
CeilingResistance = 0.00
WallResistance = 0.05

CWalls = 10600
Rtot = 0.073
FluidSpecHeat = 4187.

TimeStep = 3600.

! Input of 24 TimeSteps (1 per hour)
DO nHour = 1,8
        Boundary(nHour).ConvHeatFlux = 30.
        Boundary(nHour).RadHeatFlux = 10.
        Boundary(nHour).RunningMode = 1
        Boundary(nHour).Twater = 20.
        Boundary(nHour).MaxCoolingPower = 1000.
        Boundary(nHour).MassFlow = 0.3
ENDDO
DO nHour = 9,19
        Boundary(nHour).ConvHeatFlux = 400.
        Boundary(nHour).RadHeatFlux = 300.
        Boundary(nHour).RunningMode = 0
        Boundary(nHour).Twater = 20.
        Boundary(nHour).MaxCoolingPower = 0.
        Boundary(nHour).MassFlow = 0.3
ENDDO
DO nHour = 20,24
        Boundary(nHour).ConvHeatFlux = 150.
```

```
        Boundary(nHour).RadHeatFlux = 100.
        Boundary(nHour).RunningMode = 1
        Boundary(nHour).Twater = 20.
        Boundary(nHour).MaxCoolingPower = 1000.
        Boundary(nHour).MassFlow = 0.3
ENDDO

! <-- Definition of the input data

hSlabToWalls = (1 - FvFloorToCeiling - FvSlabToExtWall) * 4 * 300**3 * 5.67/10**8 * 0.9
hFloorToCeiling = FvFloorToCeiling * 4 * 300**3 * 5.67/10**8 * 0.9

nThNodes = 0
DO nLayer = 1, nLayersUp + nLayersDown
        DO nDivision = 1, Layer(nLayer).nDivisions
                IF ((nLayer.EQ.1) .AND. (nDivision.EQ.1)) THEN
                        nThNodes = nThNodes + 1
                        ThNode(nThNodes).ThInertia = 0.
                        ThNode(nThNodes).RUp = 0.
                        ThNode(nThNodes).RDown = FloorResistance
                        ThNode(nThNodes).Position = "F" ! Floor
                ENDIF
                nThNodes = nThNodes + 1
                ThNode(nThNodes).ThInertia = Layer(nLayer).Thickness / Layer(nLayer).nDivisions * Layer(nLayer).Density * Layer(nLayer).SpecHeat
                ThNode(nThNodes).RUp = Layer(nLayer).Thickness / (2. * Layer(nLayer).nDivisions * Layer(nLayer).ThCond)
                ThNode(nThNodes).RDown = Layer(nLayer).Thickness / (2. * Layer(nLayer).nDivisions * Layer(nLayer).ThCond)
                ThNode(nThNodes).Position = "I" ! Internal
                IF ((nLayer.EQ.nLayersUp).AND.(nDivision.EQ.Layer(nLayersUp).nDivisions)) THEN
                        nThNodes = nThNodes + 1
                        ThNode(nThNodes).ThInertia = 0.
                        ThNode(nThNodes).RUp = 0.
                        ThNode(nThNodes).RDown = 0.
                        ThNode(nThNodes).Position = "P" ! PipeLevel
                        nThNode_PipeLevel = nThNodes
                ENDIF
                IF ((nLayer.EQ.nLayersUp + nLayersDown).AND.(nDivision.EQ.Layer(nLayersUp + nLayersDown).nDivisions)) THEN
                        nThNodes = nThNodes + 1
                        ThNode(nThNodes).ThInertia = 0.
                        ThNode(nThNodes).RUp = CeilingResistance
                        ThNode(nThNodes).RDown = 0.
                        ThNode(nThNodes).Position = "C" ! Ceiling
                ENDIF
        ENDDO
ENDDO
nThNodes = nThNodes + 1
ThNode(nThNodes).ThInertia = 0.
ThNode(nThNodes).RUp = 0.
ThNode(nThNodes).RDown = WallResistance
ThNode(nThNodes).Position = "S" ! Surface (of the wall)
nThNodes = nThNodes + 1
ThNode(nThNodes).ThInertia = CWalls
ThNode(nThNodes).RUp = 0.
ThNode(nThNodes).RDown = 0.
ThNode(nThNodes).Position = "K" ! Wall inner Side
nThNodes = nThNodes + 1
ThNode(nThNodes).ThInertia = 0.
ThNode(nThNodes).RUp = 0.
ThNode(nThNodes).RDown = 0.
ThNode(nThNodes).Position = "A" !Air
```

```
DO nThNode = 1,nThNodes
    IF (ThNode(nThNode).Position.EQ."F") THEN
        ThNode(nThNode).Coeff_Air = hAirToFloor * FloorArea
        ThNode(nThNode).Coeff_Wall = hSlabToWalls * FloorArea
        ThNode(nThNode).Coeff_Floor = 0.
        ThNode(nThNode).Coeff_Ceiling = hFloorToCeiling * FloorArea
        ThNode(nThNode).Coeff_Rad = FloorArea / (2. * FloorArea + WallArea)
        ThNode(nThNode).Coeff_Conv = 0.
        ThNode(nThNode).Coeff_CondUp = 0.
        ThNode(nThNode).Coeff_CondDown = 1 / (ThNode(nThNode).RDown + ThNode(nThNode + 1).RUp) * FloorArea
        ThNode(nThNode).Coeff_Inertia = 0.
        ThNode(nThNode).Coeff_Circuit = 0.
    ENDIF
    IF (ThNode(nThNode).Position.EQ."I") THEN
        ThNode(nThNode).Coeff_Air = 0.
        ThNode(nThNode).Coeff_Wall = 0.
        ThNode(nThNode).Coeff_Floor = 0.
        ThNode(nThNode).Coeff_Ceiling = 0.
        ThNode(nThNode).Coeff_Rad = 0.
        ThNode(nThNode).Coeff_Conv = 0.
        ThNode(nThNode).Coeff_CondUp = 1 / (ThNode(nThNode - 1).RDown + ThNode(nThNode).RUp) * FloorArea
        ThNode(nThNode).Coeff_CondDown = 1 / (ThNode(nThNode).RDown + ThNode(nThNode + 1).RUp) * FloorArea
        ThNode(nThNode).Coeff_Inertia = ThNode(nThNode).ThInertia * FloorArea / TimeStep
        ThNode(nThNode).Coeff_Circuit = 0.
    ENDIF
    IF (ThNode(nThNode).Position.EQ."P") THEN
        ThNode(nThNode).Coeff_Air = 0.
        ThNode(nThNode).Coeff_Wall = 0.
        ThNode(nThNode).Coeff_Floor = 0.
        ThNode(nThNode).Coeff_Ceiling = 0.
        ThNode(nThNode).Coeff_Rad = 0.
        ThNode(nThNode).Coeff_Conv = 0.
        ThNode(nThNode).Coeff_CondUp = 1 / (ThNode(nThNode - 1).RDown + ThNode(nThNode).RUp) * FloorArea
        ThNode(nThNode).Coeff_CondDown = 1 / (ThNode(nThNode).RDown + ThNode(nThNode + 1).RUp) * FloorArea
        ThNode(nThNode).Coeff_Inertia = 0.
        ThNode(nThNode).Coeff_Circuit = 1 / RTot * FloorArea
    ENDIF
    IF (ThNode(nThNode).Position.EQ."C") THEN
        ThNode(nThNode).Coeff_Air = hAirToCeiling * FloorArea
        ThNode(nThNode).Coeff_Wall = hSlabToWalls * FloorArea
        ThNode(nThNode).Coeff_Floor = hFloorToCeiling * FloorArea
        ThNode(nThNode).Coeff_Ceiling = 0.
        ThNode(nThNode).Coeff_Rad = FloorArea / (2. * FloorArea + WallArea)
        ThNode(nThNode).Coeff_Conv = 0.
        ThNode(nThNode).Coeff_CondUp = 1 / (ThNode(nThNode - 1).RDown + ThNode(nThNode).RUp) * FloorArea
        ThNode(nThNode).Coeff_CondDown = 0.
        ThNode(nThNode).Coeff_Inertia = 0.
        ThNode(nThNode).Coeff_Circuit = 0.
    ENDIF
    IF (ThNode(nThNode).Position.EQ."S") THEN
        ThNode(nThNode).Coeff_Air = hAirToWalls * WallArea
        ThNode(nThNode).Coeff_Wall = 0.
        ThNode(nThNode).Coeff_Floor = hSlabToWalls * FloorArea
        ThNode(nThNode).Coeff_Ceiling = hSlabToWalls * FloorArea
        ThNode(nThNode).Coeff_Rad = WallArea / (2. * FloorArea + WallArea)
        ThNode(nThNode).Coeff_Conv = 0.
        ThNode(nThNode).Coeff_CondUp = 0.
        ThNode(nThNode).Coeff_CondDown = 1 / (ThNode(nThNode).RDown + ThNode(nThNode + 1).RUp) * WallArea
        ThNode(nThNode).Coeff_Inertia = 0.
        ThNode(nThNode).Coeff_Circuit = 0.
```

```
        ENDIF
        IF (ThNode(nThNode).Position.EQ."K") THEN
                ThNode(nThNode).Coeff_Air = 0.
                ThNode(nThNode).Coeff_Wall = 0.
                ThNode(nThNode).Coeff_Floor = 0.
                ThNode(nThNode).Coeff_Ceiling = 0.
                ThNode(nThNode).Coeff_Rad = 0.
                ThNode(nThNode).Coeff_Conv = 0.
                ThNode(nThNode).Coeff_CondUp = 1 / (ThNode(nThNode - 1).RDown + ThNode(nThNode).RUp) * WallArea
                ThNode(nThNode).Coeff_CondDown = 0.
                ThNode(nThNode).Coeff_Inertia = ThNode(nThNode).ThInertia * WallArea / TimeStep
                ThNode(nThNode).Coeff_Circuit = 0.
        ENDIF
        IF (ThNode(nThNode).Position.EQ."A") THEN
                ThNode(nThNode).Coeff_Air = 0.
                ThNode(nThNode).Coeff_Wall = hAirToWalls * WallArea
                ThNode(nThNode).Coeff_Floor = hAirToFloor * FloorArea
                ThNode(nThNode).Coeff_Ceiling = hAirToCeiling * FloorArea
                ThNode(nThNode).Coeff_Rad = 0.
                ThNode(nThNode).Coeff_Conv = 1.
                ThNode(nThNode).Coeff_CondUp = 0.
                ThNode(nThNode).Coeff_CondDown = 0.
                ThNode(nThNode).Coeff_Inertia = 0.
                ThNode(nThNode).Coeff_Circuit = 0.
        ENDIF
ENDDO

TolDailyMax = 0.0001
nItDailyMax = 500
TolHourlyMax = 0.00001
nItHourlyMax = 1000
nItDaily = 0
TolDaily = 100000.

SumOfTemps = 0.
DO nThNode = 1,nThNodes
        ThNode(nThNode).Temp = 22.
        SumOfTemps = SumOfTemps + 24 * ThNode(nThNode).Temp
ENDDO

DO WHILE ((nItDaily.LT.nItDailyMax).AND.(TolDaily.GT.TolDailyMax))
        nItDaily = nItDaily + 1
        SumOfTemps_Prev = SumOfTemps
        SumOfTemps = 0.
        TolDaily = 0.
        DO nHour = 1,24
                nItHourly = 0
                TolHourly = 100000.
                DO nThNode = 1,nThNodes
                        ThNode(nThNode).PrevTemp = ThNode(nThNode).Temp
                ENDDO
                DO WHILE ((nItHourly.LT.nItHourlyMax).AND.(TolHourly.GT.TolHourlyMax))
                        TolHourly = 0.
                        nItHourly = nItHourly + 1
                        QCircuit = 0.
                        DO nThNode = 1,nThNodes
                                TAir = ThNode(nThNodes).Temp
                                TFloor = ThNode(1).Temp
                                TCeiling = ThNode(nThNodes - 3).Temp
                                TWalls = ThNode(nThNodes - 2).Temp
```

```
                TPipeLevel = ThNode(nThNode_PipeLevel).Temp
                IF (Boundary(nHour).MassFlow.GT.0.) THEN
                    TWater = max(Boundary(nHour).TWater, TWater - (QCircuit + Boundary(nHour).MaxCoolingPower) / (Boundary(nHour).MassFlow * FluidSpecHeat))
                ELSE
                    TWater = Boundary(nHour).TWater
                ENDIF
                A = 0.
                B = 0.
                A = ThNode(nThNode).Coeff_Air * TAir + &
                        ThNode(nThNode).Coeff_Wall * TWalls + &
                        ThNode(nThNode).Coeff_Floor * TFloor + &
                        ThNode(nThNode).Coeff_Ceiling * TCeiling + &
                        ThNode(nThNode).Coeff_Rad * Boundary(nHour).RadHeatFlux + &
                        ThNode(nThNode).Coeff_Conv * Boundary(nHour).ConvHeatFlux + &
                        ThNode(nThNode).Coeff_Inertia * ThNode(nThNode).PrevTemp + &
                        ThNode(nThNode).Coeff_Circuit * Boundary(nHour).RunningMode * TWater
                B = ThNode(nThNode).Coeff_Air + &
                        ThNode(nThNode).Coeff_Wall + &
                        ThNode(nThNode).Coeff_Floor + &
                        ThNode(nThNode).Coeff_Ceiling + &
                        0. + &
                        0. + &
                        ThNode(nThNode).Coeff_Inertia + &
                        ThNode(nThNode).Coeff_Circuit * Boundary(nHour).RunningMode
                IF (ThNode(nThNode).Position.NE."F") THEN
                    A = A + ThNode(nThNode).Coeff_CondUp * ThNode(nThNode - 1).Temp
                    B = B + ThNode(nThNode).Coeff_CondUp
                ENDIF
                IF (ThNode(nThNode).Position.NE."A") THEN
                    A = A + ThNode(nThNode).Coeff_CondDown * ThNode(nThNode + 1).Temp
                    B = B + ThNode(nThNode).Coeff_CondDown
                ENDIF
                SuppTemp = A / B
                TolHourly = TolHourly + ABS(SuppTemp - ThNode(nThNode).Temp)
                ThNode(nThNode).Temp = SuppTemp
                QCircuit = ThNode(nThNode_PipeLevel).Coeff_Circuit * Boundary(nHour).RunningMode * (TWater - TPipeLevel)
            ENDDO
            Boundary(nHour).TAir = ThNode(nThNodes).Temp
            Boundary(nHour).TFloor = ThNode(1).Temp
            Boundary(nHour).TPipeLevel = ThNode(nThNode_PipeLevel).Temp
            Boundary(nHour).TCeiling = ThNode(nThNodes - 3).Temp
            Boundary(nHour).TWalls = ThNode(nThNodes - 2).Temp
            Boundary(nHour).TWater = TWater
            Boundary(nHour).QFloor = ThNode(1).Coeff_Air * Boundary(nHour).TAir + &
                    ThNode(1).Coeff_Wall * Boundary(nHour).TWalls + &
                    ThNode(1).Coeff_Ceiling * Boundary(nHour).TCeiling + &
                    ThNode(1).Coeff_Rad * Boundary(nHour).RadHeatFlux - &
                    (ThNode(1).Coeff_Air + ThNode(1).Coeff_Wall + ThNode(1).Coeff_Ceiling) * Boundary(nHour).TFloor
            Boundary(nHour).QCeiling = ThNode(nThNodes - 3).Coeff_Air * Boundary(nHour).TAir + &
                    ThNode(nThNodes - 3).Coeff_Wall * Boundary(nHour).TWalls + &
                    ThNode(nThNodes - 3).Coeff_Floor* Boundary(nHour).TFloor + &
                    ThNode(nThNodes - 3).Coeff_Rad * Boundary(nHour).RadHeatFlux - &
                    (ThNode(nThNodes - 3).Coeff_Air + ThNode(nThNodes - 3).Coeff_Wall + ThNode(nThNodes - 3).Coeff_Floor) * Boundary(nHour).TCeiling
            Boundary(nHour).QWalls = ThNode(nThNodes - 2).Coeff_Air * Boundary(nHour).TAir + &
                    ThNode(nThNodes - 2).Coeff_Floor* Boundary(nHour).TFloor + &
                    ThNode(nThNodes - 2).Coeff_Ceiling * Boundary(nHour).TCeiling + &
                    ThNode(nThNodes - 2).Coeff_Rad * Boundary(nHour).RadHeatFlux - &
```

```
                        (ThNode(nThNodes - 2).Coeff_Air + ThNode(nThNodes - 2).Coeff_Floor + ThNode(nThNodes - 2).Coeff_Ceiling) *
Boundary(nHour).TWalls
                    Boundary(nHour).QCircuit    =    ThNode(nThNode_PipeLevel).Coeff_Circuit    *    Boundary(nHour).RunningMode    *
(Boundary(nHour).TWater - Boundary(nHour).TPipeLevel)
                ENDDO
                DO nThNode = 1,nThNodes
                    SumOfTemps = SumOfTemps + ABS(ThNode(nThNodes).Temp)
                ENDDO
            ENDDO
            TolDaily = ABS(SumOfTemps_Prev - SumOfTemps)
        ENDDO
        SumOfConv = 0.
        SumOfRad = 0.
        SumOfQFloor = 0.
        SumOfQCeiling = 0.
        SumOfQWalls = 0.
        SumOfQCircuit = 0.
        DO nHour = 1, 24
            WRITE(*,*)
            WRITE(*,*) 'nHour: ', nHour
            WRITE(*,*) ' TWater: ', Boundary(nHour).TWater, '°C'
            WRITE(*,*) ' TPipeLevel: ', Boundary(nHour).TPipeLevel, '°C -    QCircuit: ', Boundary(nHour).QCircuit
            WRITE(*,*) ' TFloor: ', Boundary(nHour).TFloor, '°C -        QFloor: ', Boundary(nHour).QFloor
            WRITE(*,*) ' TCeiling: ', Boundary(nHour).TCeiling, '°C -    QCeiling: ', Boundary(nHour).QCeiling
            WRITE(*,*) ' TWalls: ', Boundary(nHour).TWalls, '°C -        QWalls: ', Boundary(nHour).QWalls
            WRITE(*,*) ' TAir: ', Boundary(nHour).TAir, '°C'
            SumOfConv = SumOfConv + Boundary(nHour).ConvHeatFlux
            SumOfRad = SumOfRad + Boundary(nHour).RadHeatFlux
            SumOfQFloor = SumOfQFloor + Boundary(nHour).QFloor
            SumOfQCeiling = SumOfQCeiling + Boundary(nHour).QCeiling
            SumOfQWalls = SumOfQWalls + Boundary(nHour).QWalls
            SumOfQCircuit = SumOfQCircuit + Boundary(nHour).QCircuit
        ENDDO
        WRITE(*,*)
        WRITE(*,*)
        WRITE(*,*)
        WRITE(*,*) 'SumOfConv: ', SumOfConv
        WRITE(*,*) 'SumOfRad: ', SumOfRad
        WRITE(*,*) 'SumOfQFloor: ', SumOfQFloor
        WRITE(*,*) 'SumOfQCeiling: ', SumOfQCeiling
        WRITE(*,*) 'SumOfQWalls: ', SumOfQWalls
        WRITE(*,*) 'SumOfQCircuit: ', SumOfQCircuit

        STOP
END
```

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