BRITISH STANDARD

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Heating systems in buildings — Design of embedded water based surface heating and cooling systems —

Part 3: Optimizing for use of renewable energy sources

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ICS 91.140.10

British Standards

National foreword

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Heating systems in buildings - Design of embedded water based surface heating and cooling systems - Part 3: Optimizing for use of renewable energy sources

Conception des systèmes de chauffage et refroidissement par le sol, le mur et le plafond - Partie 3 : Optimisation pour l'usage des sources d'énergie renouvelable

Heizungsanlagen in Gebäuden - Planung von eingebetteten Flächenheiz- und -kühlsystemen mit Wasser als Arbeitsmedium - Teil 3: Optimierung für die Nutzung erneuerbarer Energiequellen

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Foreword

This document (EN 15377-3:2007) has been prepared by Technical Committee CEN/TC 228 "Heating systems in buildings", the secretariat of which is held by DS.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by April 2008, and conflicting national standards shall be withdrawn at the latest by April 2008.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association (Mandate M/343), and supports essential requirements of EU Directive 2002/91/EC on the energy performance of buildings (EPBD). It forms part of a series of standards aimed at European harmonisation of the methodology for calculation of the energy performance of buildings. An overview of the whole set of standards is given in prCEN/TR 15615.

The subjects covered by CEN/TC 228 are the following:

- design of heating systems (water based, electrical etc.);
- installation of heating systems;
- commissioning of heating systems;
- instructions for operation, maintenance and use of heating systems;
- methods for calculation of the design heat loss and heat loads;
- methods for calculation of the energy performance of heating systems.

Heating systems also include the effect of attached systems such as hot water production systems.

All these standards are systems standards, i.e. they are based on requirements addressed to the system as a whole and not dealing with requirements to the products within the system.

Where possible, reference is made to other European or International Standards, a.o. product standards. However, use of products complying with relevant product standards is no guarantee of compliance with the system requirements.

The requirements are mainly expressed as functional requirements, i.e. requirements dealing with the function of the system and not specifying shape, material, dimensions or the like.

The guidelines describe ways to meet the requirements, but other ways to fulfil the functional requirements might be used if fulfilment can be proved.

Heating systems differ among the member countries due to climate, traditions and national regulations. In some cases requirements are given as classes so national or individual needs may be accommodated.

In cases where the standards contradict with national regulations, the latter should be followed.

prEN 15377 *Heating systems in buildings – Design of embedded water based surface heating and cooling systems* consists of the following parts:

Part 1: Determination of the design heating and cooling capacity

Part 2: Design, dimensioning and installation

Part 3: Optimizing for use of renewable energy sources

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

Introduction

The aim of the present standard is to give a guide for the design of water based embedded heating and cooling systems to promote the use of renewable energy sources and to provide a method for actively integrating the building mass to reduce peak loads, transfer heating/cooling loads to off-peak time periods and to decrease systems size.

A section in the present standard describes how the design and dimensioning can be improved to facilitate renewable energy sources.

Peak loads can be reduced by activating the building mass using pipes embedded in the main concrete structure of the building (**T**hermo-**A**ctive-**B**uilding-**S**ystems, TABS). For this type of systems, the steady state calculation of heating and cooling capacity (part 1 of this standard) is not sufficient. Thus, several sections of this standard describe methods for taken into account the dynamic behavior.

The proposed methods are used to calculate and verify that the cooling capacity of the system is sufficient and to calculate the cooling requirements on the water side for sizing the cooling system.

The energetic assessment of surface heating and cooling systems may also be carried out according to national guidelines accomplishing the goal of this standard.

1 Scope

This document is applicable to water based 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.

The methods do not apply to heated or chilled ceiling panels or beams.

This standard is part 3 of a series of standards:

— *Part 1: Determination of the design heating and cooling capacity*;

— *Part 2: Design, dimensioning and installation*;

— *Part 3:Optimizing for use of renewable energy sources*.

The aim of the present standard is to give a guide for the design to promote the use of renewable energy sources and to provide a method for the use of Thermo-Active-Building-Systems (TABS).

The method allows calculation of peak cooling capacity of a thermo-active system, based on heat gains (solar, internal loads, ventilation).

This method also allows calculation of the energy demand on the water side (system) to be used for sizing of the cooling system, e.g. chiller, fluid flow rate.

Steady state heating capacity is calculated according to method B or E of prEN 15377-1 (part 1 of this series of standards).

2 Normative references

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

EN 15251, *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*

EN 15255, *Thermal performance of buildings – Sensible room cooling load calculation – General criteria and validation procedures*

EN 15265, *Energy performance of buildings - Calculation of energy needs for space heating and cooling using dynamic methods - General criteria and validation procedures*

prEN 15377-1:2005, *Heating systems in buildings – Design of embedded water based surface heating and cooling systems — Part 1: Determination of the design heating and cooling capacity*

prEN 15377-2, *Heating systems in buildings — Design of embedded water based surface heating and cooling systems — Part 2: Design, dimensioning and installation*

3 Terms, definitions and symbols

For the purposes of this document, the terms and definitions given in prEN 15377-1:2005 and the following symbols apply.

3.1 Data referred to the circuit:

$\dot{m}_{H,sp}$	specific water flow, calculated on the area covered by the circuit kg/ (m^2 s) ;
c_w	specific heat capacity of the water J/ (kg K) ;
T	pipe spacing m ;
d_a	external diameter of the pipe m ;
s_r	thickness of the pipe wall m ;
λ_r	thermal conductivity of the material of the pipe wall W/ (m K) ;
A_{Floor}	area cooled/heated by the circuit m^2 ;
L_R	length of the circuit m ;
P_W^{Max}	maximum cooling (<0) or heating (>0) power for a conditioning plant W ;
θ_w^0	supply water temperature at the beginning of the simulation °C ;
$\theta_w^{\lim}$	minimum (in the cooling case) or maximum (in the heating case) supply water temperature obtainable by the machine °C .

3.2 Data referred to the room geometry and the boundary conditions:

A_{Walls}	overall area of vertical walls, external facade excluded m^2 ;
$F_{v\ Floor\text{-}Ext\ Wall}$	view factor floor-external wall;
$F_{v\ Floor\text{-}Ceiling}$	view factor floor-ceiling;
$F_{v\ Floor\text{-}Walls}$	view factor floor-walls;
$R_{add\ Floor}$	additional resistance covering the upper side of the slab (m^2 K)/W ;
$R_{add\ Ceiling}$	additional resistance covering the lower side of the slab (m^2 K)/W ;
R_{Walls}	resistance of the surface layer of internal walls (m^2 K)/W ;
$h_{Air\text{-}Floor}$	convective heat transfer coefficient between the air and the floor W/(m^2 K) ;
$h_{Air\text{-}Ceiling}$	convective heat transfer coefficient between the air and the ceiling W/(m^2 K) ;
$h_{Air\text{-}Walls}$	convective heat transfer coefficient between the air and the internal walls W/(m^2 K) ;
$h_{Floor\text{-}Walls}$	radiant heat transfer coefficient between the floor and the internal walls W/(m^2 K) ;
$h_{Floor\text{-}Ceiling}$	radiant heat transfer coefficient between the floor and the ceiling W/(m^2 K) ;
$h_{Ceiling\text{-}Walls}$	radiant heat transfer coefficient between the ceiling and the internal walls W/(m^2 K) ;
C_{Walls}	average specific thermal inertia of the internal walls J/(m^2 K)
Δt	calculation time step s .

The following data shall be known for all the day, and the values during the n-th time step from the beginning of the simulation have to be defined:

$T_{comfort}$	maximum operative temperature allowed for comfort conditions °C ;
$\dot{Q}^{n}_{Sun}$	solar gain in the room in the present calculation time step W ;
$\dot{Q}^{n}_{Transm}$	incoming heat flux to the room from the external wall in the present calculation time step W ;
$\dot{Q}^{n}_{Air}$	convective heat flux extracted by the air circuit W ;
$\dot{Q}^{n}_{IntRad}$	internal radiant heat gain due to people or electrical equipment in the present calculation time step W ;
$\dot{Q}^{n}_{IntConv}$	internal convective heat gain due to people or electrical equipment in the present calculation time step W ;
f^{n}_{rm}	running mode (the value is 1 when the system is running and 0 when the system is switched off) dimensionless ;

3.3 Data referred to the slab and its partitions:

s_1	thickness of the upper part of the slab m ;
s_2	thickness of the lower part of the slab m ;
J_1	number of material layers constituting the upper part of the slab dimensionless ;
J_2	number of material layers constituting the lower part of the slab dimensionless ;

As a consequence, $J=J_1+J_2$ represents the total number of material layers constituting the slab and J sets of physical properties (ρ_j, c_j, λ_j, δ_j, m_j, R_j) shall be known or chosen, where:

ρ_j	density of the material constituting the j-th layer kg/m^3 ;
c_j	specific heat capacity of the material constituting the j-th layer J/ (kg K) ;
λ_j	thermal conductivity of the j-th layer W/ (m K) ;
δ_j	thickness of the j-th layer m , $\delta_j = 0$ if the layer is a mere thermal resistance;
m_j	number of partitions of the j-th layer dimensionless ;
R_j	thermal resistance summarizing the j-th layer m^{2}K/W , $R_j > 0$ if the layer is a mere thermal resistance.

For geometrical consistency: $\sum_{j=1}^{J_1} \delta_j = s_1 \quad and \quad \sum_{j=J_1}^{J_1+J_2} \delta_j = s_2$.

3.4 Data referred to the initial temperature profile

The initial value of the supply water temperature (θ^{0}_{w}) and the interface temperatures of partitions of the slab ($\theta^{0}_{\mathrm{I,i}}$ with $0 \le i \le i_L$) shall be decided. As for the slab, a possible choice could be assigning the same value to all the interfaces, equal to the mean temperature at the start of the simulation.

However, if the simulation covers more than one running cycle, the choice of the initial values is not decisive. In fact, it will influence only the very first time steps of the simulation.

3.5 Calculation of the temperature profile and the heat fluxes in the generic time-step n

The temperature reached at a certain interface at the end of the previous time step is used for calculation of the heat fluxes acting on the building structures and for calculation of the consequent temperatures at the end of the time step in progress. These magnitudes are:

$\dot{q}^{n}_{Conv}$	global specific convective heat gains W/m^2 ;
$\dot{q}^{n}_{Rad}$	global specific radiant heat gains W/m^2 ;
θ^{n}_{Air}	air temperature in the room in the present calculation time step °C ;
θ^{n}_{Walls}	mean temperature of the walls in the present calculation time step °C ;
θ^{n}_{Op}	operative temperature in the room in the present calculation time step °C ;
θ^{n-1}_{w}	supply water temperature at the end of the previous time step °C ;
$\theta^{n-1}_{w\ exit}$	outlet water temperature at the end of the previous time step °C ;
$\theta^{n-1}_{I,i}$	temperature of the i-th interface, with $0 \le i \le i_L$, at the end of the previous time step, °C ;

The results obtained at every time step are:

θ^{n}_{w}	supply water temperature at the end of the time step in progress °C ;
θ^{n}_{F} , θ^{n}_{s}	temperature of the upper and lower sides of the slab at the end of the time step in progress °C ;
$\theta^{n}_{I,i}$	temperature of the i-th interface, with $0 \le i \le i_L$, at the end of the time step in progress, °C .

4 Relation to other EPBD standards

The present standard requires input from the following standards: prEN 15377-1, EN 15251, EN 15255 and EN 15265.

The present standard provides input data to the following standards: EN 15243 and EN ISO 13792.

5 Optimisation of systems for facilitating the use of renewable energy sources

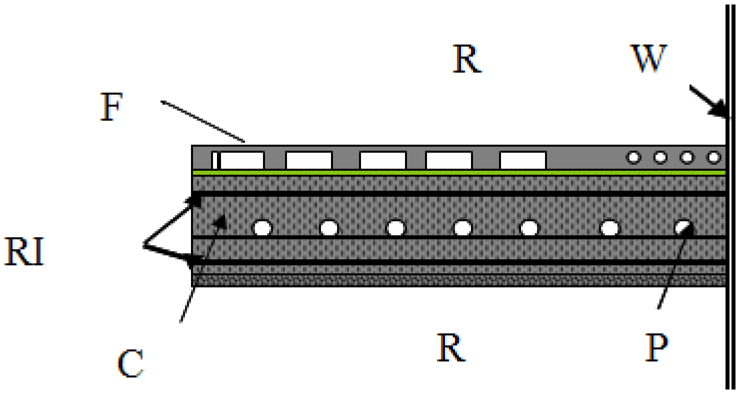
Transporting energy by water uses less auxiliary energy for pumps and less installation space than carrying the same amount of energy by air. A further optimizing is to use water at temperatures close to room temperature for heating and cooling: low temperature heating - high temperature cooling.

For normal embedded radiant floor-, wall-, and ceiling heating/cooling systems, increasing the pipe spacing and decreasing the difference between supply and return water temperature results in water temperatures closer to room temperature, but this increases flow rates and pipe lengths leading to higher pressure losses. This forces designers to choose between either increasing auxiliary energy use for pumps or applying pipes with a larger diameter, both of which are undesirable options. This can partly be compensated by using more circuits of shorter pipe lengths. These factors shall be optimized according to prEN 15377-2 (part 2 of this series of standards).

For Thermo-Active-Building–Systems, a further optimization regarding use of renewable energy sources is made by reducing the peak load, transferring the load to off-peak time periods, downsizing of energy generation systems, and increased efficiency of energy generation due to water temperature level. This facilitates the possible use of energy sources such as solar collectors, ground source heat pumps, free cooling, ground source heat exchangers, aquifers.

6 The concept of Thermo-Active-Building-Systems (TABS)

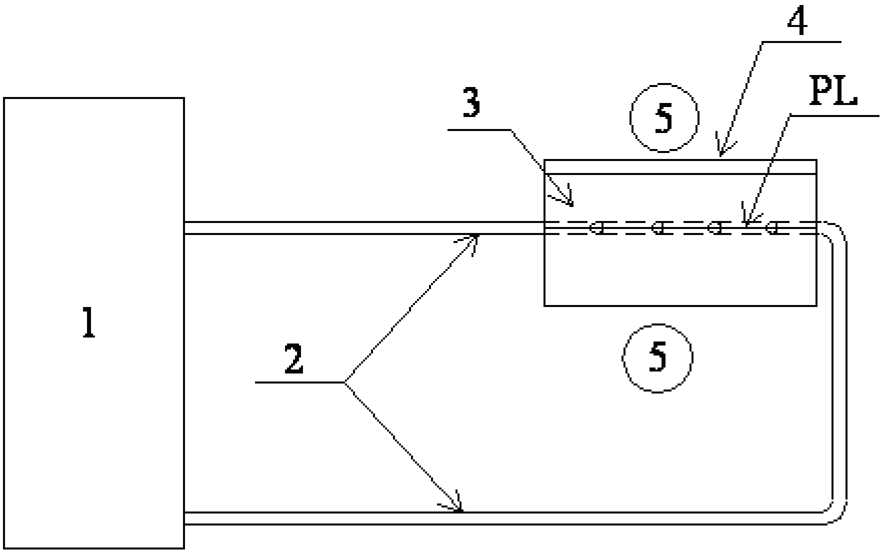
A Thermo-Active-Building-System (TABS) is a water based heating and cooling system, where the pipes are embedded in the central concrete core of a building construction (see Figure 1). The heat transfer takes place between the water (pipes) and the concrete, between the concrete core and the surfaces to the room (ceiling, floor) and between the surfaces and the room.



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

Figure 1 – Thermo-active radiant system

Looking at a typical structure of a thermo-active system, heat is removed by a cooling system (e.g. chiller, heat pump) connected to pipes embedded in the slab. The system can be divided into the following elements (see Figure 2):



where:

PL = pipes level

1 = cooling system (machine)

2 = hydraulic circuit

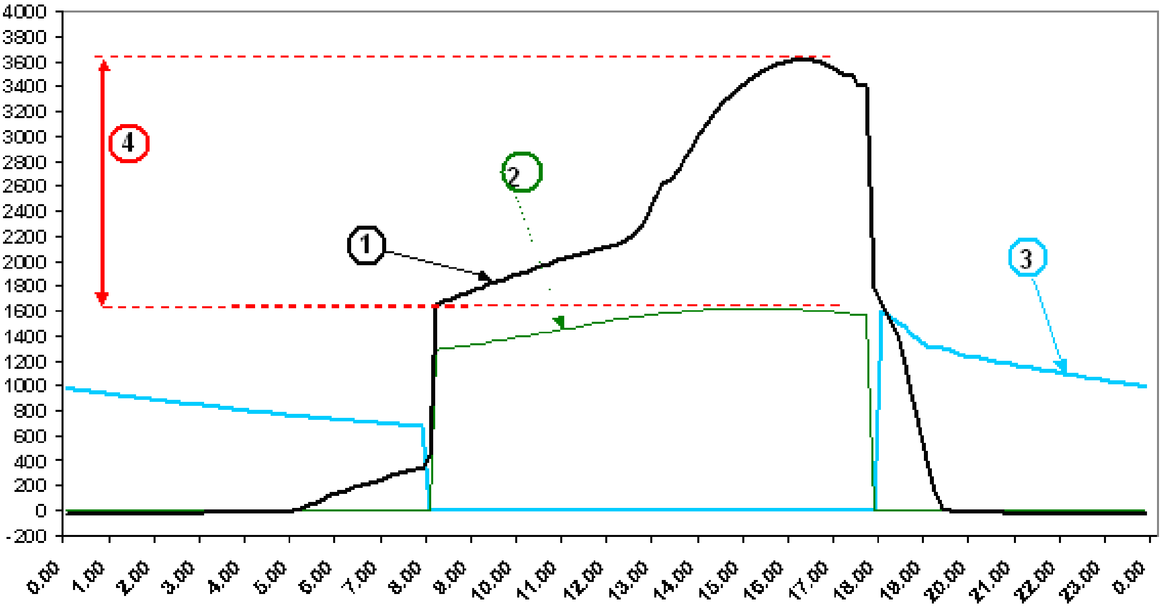
3 = slab including core level with pipes

4 = possible additional resistances (floor covering or suspended ceiling)

5 = room below and room above

Figure 2 – Simple scheme of a thermo-active system

Peak-shaving is the possibility to heat and cool the structures of the building during a period in which the occupants may be absent (e.g. during night time), reducing also the peak of the required power (see Figure 3). In this way, energy consumption may be reduced and a lower night time electricity rate (if obtainable) can be exploited, and furthermore, downsizing of the cooling system, including the chiller, is possible.



Key

1	heat gain	X-axis	time of the day
2	power needed for conditioning the ventilation air	Y-axis	cooling power
3	power needed on the water side		
4	peak of the required power reduction		

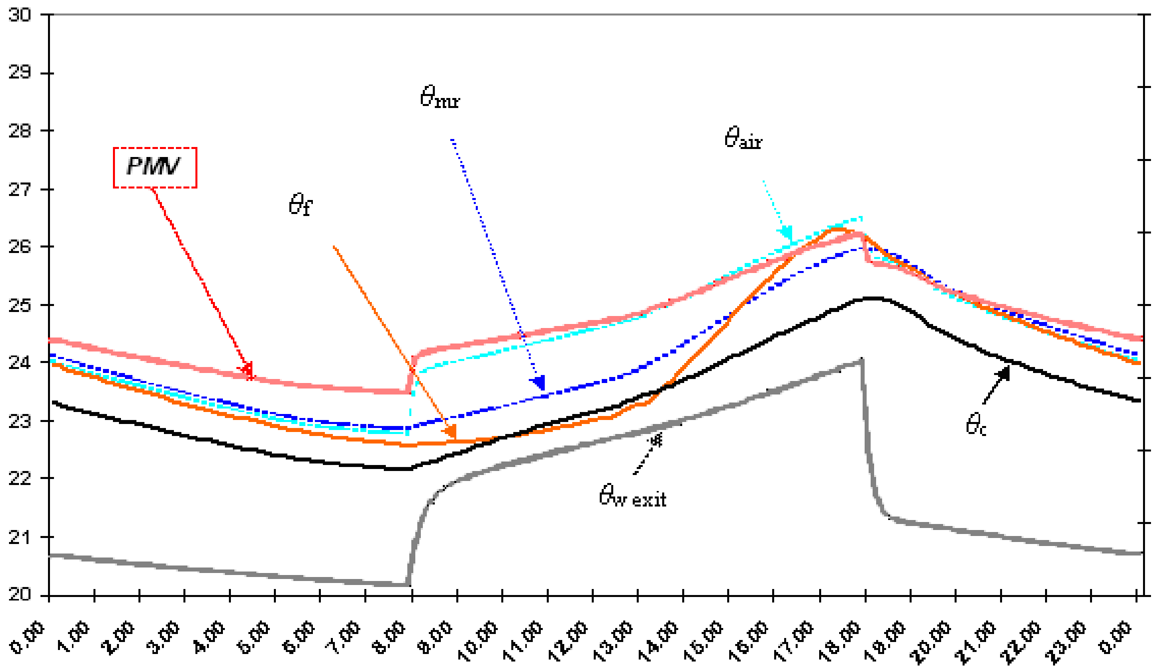
Figure 3 – Example of peak-shaving effect

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 cooling power needed for dehumidifying the air during day time is sufficient for cooling the slab during night time.

The designer needs to know if the capacity at a given water temperature is sufficient to keep the room temperature in a given range. The designer needs also to know the heat flow on the water side to be able to dimension the heat distribution system and the chiller/boiler. The present document provides methods for this.

Some detailed building-systems calculation models have been developed, e.g. for determination of the heat exchanges under non-steady state conditions in a single room, for determination of thermal and hygrometric balance of the room air, for prediction of comfort conditions, for checking of condensation on surfaces, for availability of control strategies and for 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. Development of a more user-friendly tool is required. Such a tool is provided in the following, which allows simulation of thermo-active systems in an easy way.

Internal temperature changes only moderately during the day, and the aim of a good design of TABS is to maintain comfort during the day within the range of comfort, i.e. –0,5 < PMV < 0,5, according to EN 15251 (see Figure 4).



Key

θ_{mr}	mean radiant temperature
θ_{air}	air temperature
θ_f	floor temperature
θ_c	ceiling temperature
$\theta_{w\ exit}$	return water temperature
PMV	Predicted Mean Vote

X-axis	time of the day
Y-axis, left	temperature °C
Y-axis, right	PMV values

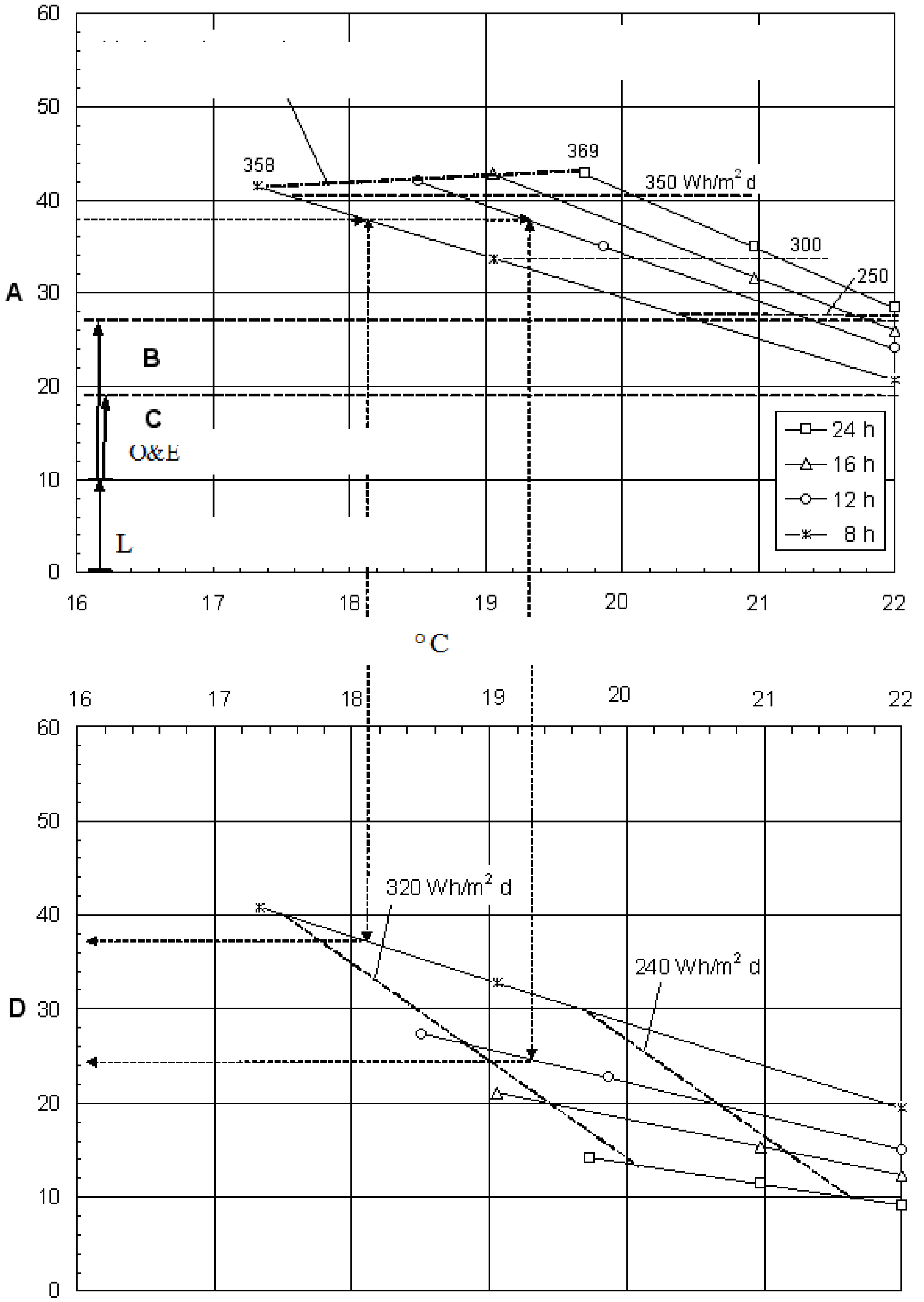
Figure 4 – Example of temperature profiles

The diagram 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 correspond to a concrete slab with raised floor (R=0,45 m^2K/W) and a permissible room temperature range of 21 °C to 26 °C.

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

The lower diagram shows the cooling power in W/m^2 required on the water side (for dimensioning of the chiller) for thermo-active slabs as a function of supply water temperature and operation time. Further, the amount of energy rejected per day is indicated in Wh/m^2 per day.

The example shows, that by 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 appr. 335 Wh/m^2 per day. The required cooling power on the water side is by 8 h operation 37 W/m^2 and by 12 h operation only 25 W/m^2. Thus, by 12 h operation, the size of the chiller can be reduced significantly. The total heat rejection on the water side is appr. 300 Wh/m^2 per day.



Key

A =Maximum total heat gain in space [W/m^2 floor area]

B = Maximum

C = Minimum

O&E = occupants and equipment (acc. to SWKI 95-3)

L = lighting (acc. to SWKI 95-3)

D =Mean cooling power tabs [W/m^2 floor area]

Figure 5 – Working principle of TABS

7 Calculation methods

7.1 General

The following calculation methods can be applied:

- rough sizing method based on a standard calculation of the cooling load (accuracy 20-30%). To be used based on the knowledge of the peak value for heat gains, see 7.2;
- simplified sizing method using diagrams based on 24 one-hour values of the heat gains (accuracy 15-20%), see 7.3;
- simplified model based on finite difference method, FDM, (accuracy 10-15%). Detailed dynamic simulation for the thermal conduction in the slab via FDM, based on 24 one-hour values of the variable cooling loads of the room as well as the temperatures of the air, see 7.4;
- detailed simulation models (accuracy 6-10%). Overall dynamic simulation model for the radiant system and the room, see 7.5.

7.2 Rough sizing method

The cooling system shall be sized for 70 % of the peak cooling load (EN 15255, prEN 15377-1 and prEN 15377-2). In this case, calculation of the cooling load has to be carried out using an operative temperature of 24 °C.

7.3 Simplified sizing method using diagrams

In this case, calculation of the heat gains has to be carried out by means of 24 hourly calculations with an operative temperature of 24 °C. If heat gains are approximated, 10 % of the solar gain has to be added each hour in order to take into account the gains due to external windows. This method is based on the assumption that the entire conductive slab is at a constant temperature during the whole day. This average temperature of the slab is calculated by the method itself and is related to the supply water temperature of the running time of the circuit.

The following data and parameters are involved by this method:

- Q, which is the specific daily heat load on the room during the design day in kWh/m^2 per day. It is the sum of the above mentioned 24 one-hour values of the heat gains divided by the floor area. The pattern of the load profile shall be known;
- $\theta_{comfort}$: maximum operative temperature allowed for comfort conditions °C;
- Exposure of the room, in order to determine when the peak load from heat gains occurs: East (morning), South (noon) or West (afternoon);
- Number of active surfaces. in order to distinguish whether the slab works by heat transfer both on the floor side and on the ceiling side or only on the ceiling side (see Figure 6);
- h: number of hours of fluid flow through the circuits h;
- R_{int}, thermal resistance of the slab in m^{2}K/W. This is the thermal resistance that connects the conductive region of the slab near the pipes level (see Figure 7) to the pipes level. In other words, it is assumed that the conductive region of the slab is maintained at a constant temperature during the occupied period (see Figure 8);

— θ_s average slab temperature in °C, which depends on the number of active surfaces, the running mode (24 h or 8 h) and the shape of the internal load profile (lunch break or not). The average surface temperature of the slab is determined through coefficients included in the method by the equation:

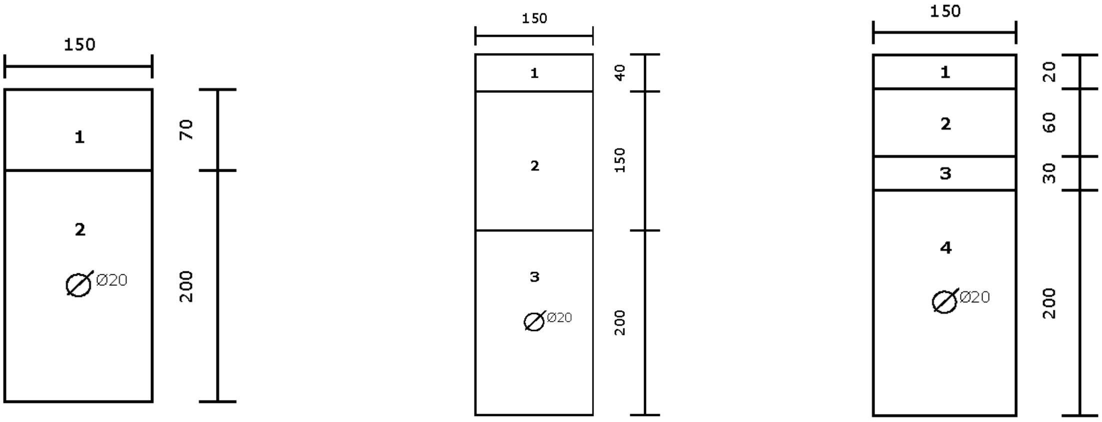
$$\theta_s = \theta_{comfort} + coeff \cdot Q \qquad \text{°C} \qquad (1)$$

where values of the coefficient are given in Table 1 and Table 2;

— R_t, total thermal resistance of the circuit in m^{2}K/W, obtained by the Resistance Method. This thermal resistance depends on the characteristics of pipe wall resistance, pipe diameter and pipe spacing (see Figure 10), and is calculated according to B.1;

— θ_w, which is the required temperature of the supply water in °C obtained through the equation:

$$\theta_w = \theta_s - \frac{Q \cdot (R_{\text{int}} + R_t) \cdot 1000}{h} \qquad \text{°C} \qquad (2)$$



where:

1 = concrete

2 = reinforced concrete

Example of slab acting through 2 surfaces

where:

1 = wood

2 = air

3 = reinforced concrete

Example of slab acting through 1 surface

where:

1 = wood

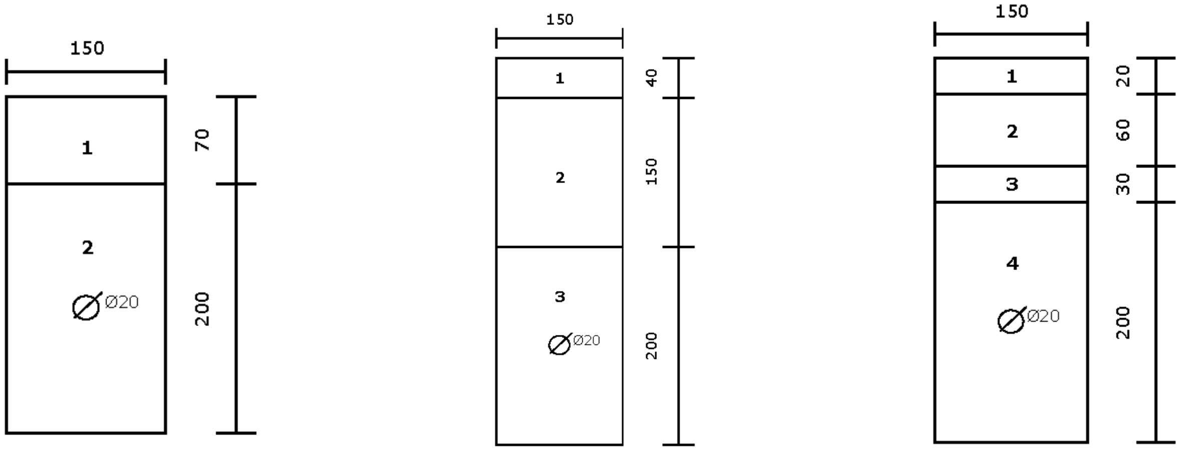
2 = concrete

3 = fibreglass

4 = reinforced concrete

Example of slab acting through 1 surface

Figure 6 – Number of active surfaces



where:

1 = concrete

2 = reinforced concrete

Conductive region:

Materials 1 and 2

where:

1 = wood

2 = air

3 = reinforced concrete

Conductive region:

Material 3

where:

1 = wood

2 = concrete

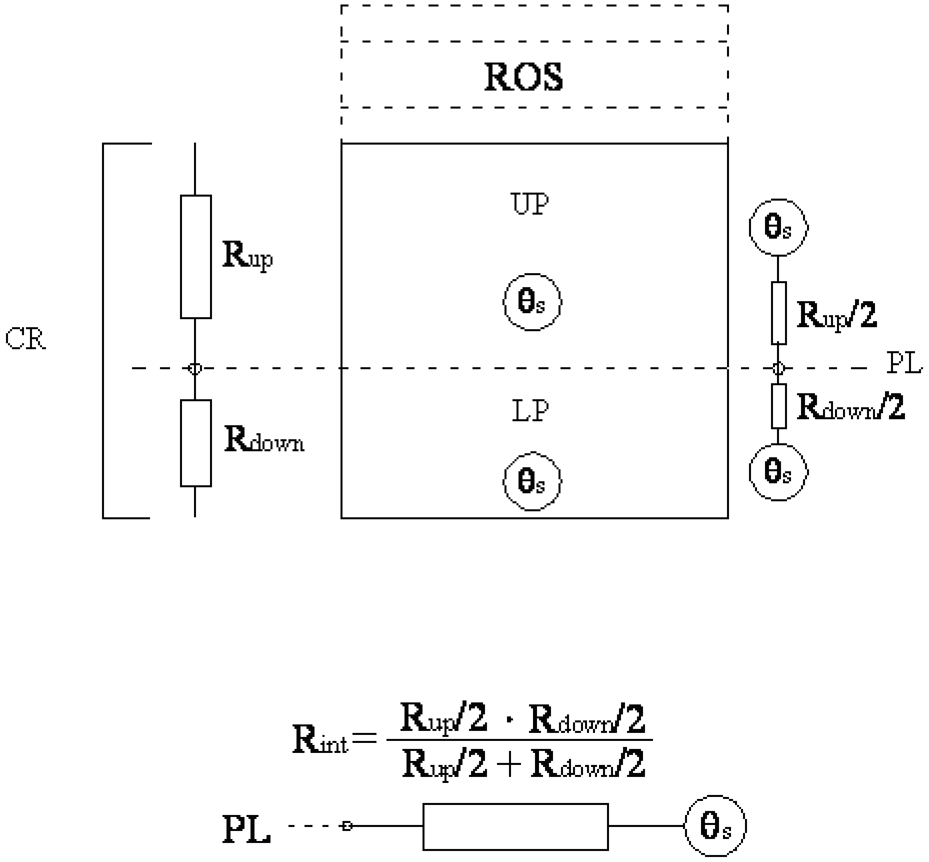
3 = fibreglass

4 = reinforced concrete

Conductive region:

Material 4

Figure 7 – Examples of conductive regions



$$R_{int} = \frac{R_{up}/2 \cdot R_{down}/2}{R_{up}/2 + R_{down}/2}$$

where:

CR = conductive region

UP = upper part of the conductive region

LP = lower part of the conductive region

ROS = rest of the slab

PL = pipes level

Figure 8 – Resistance diagram

The coefficients for calculation of the average temperature of the slab are given in Table 1 and Table 2, depending on the shape of the internal heat gains profile.

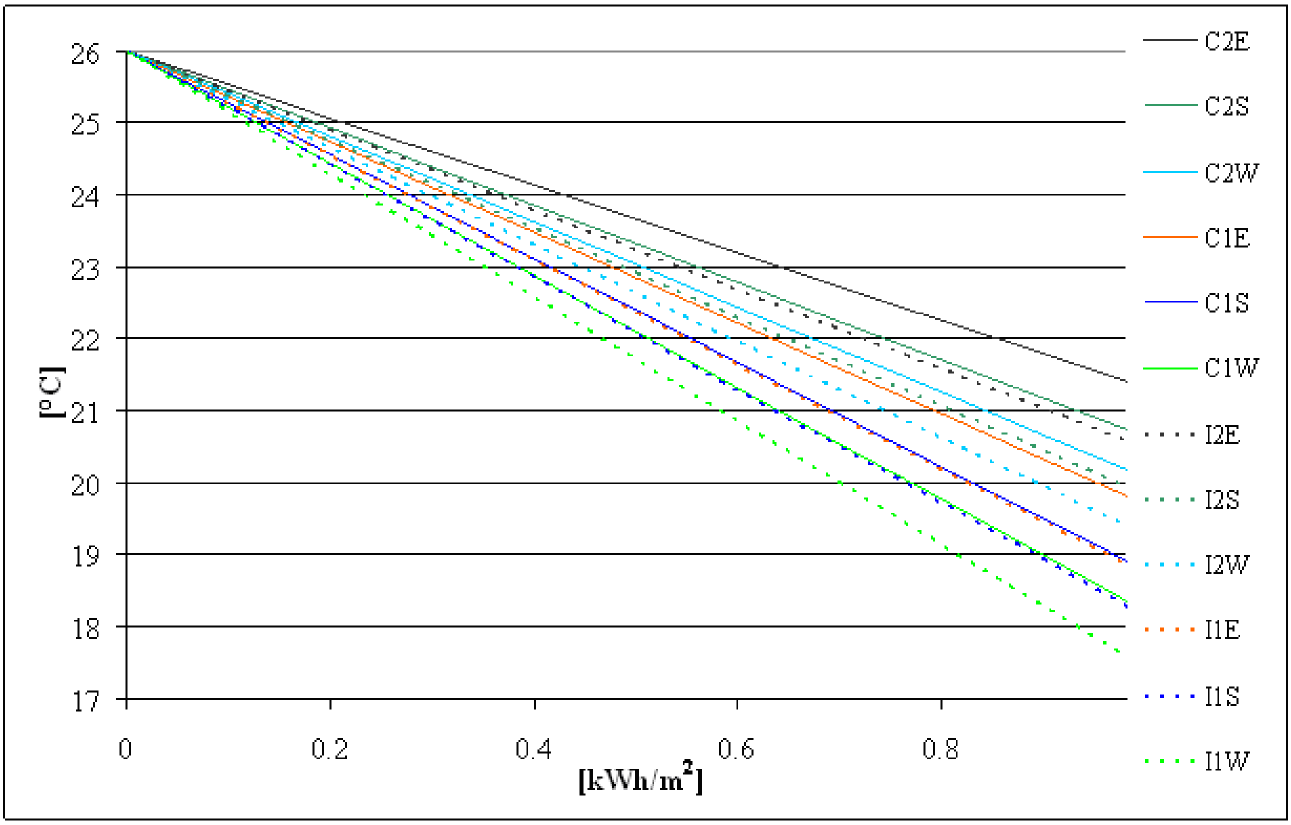
Table 1 - Constant internal heat gains from 8:00 to 18:00

	Kind of floor	Exposure of the room		
		EAST	SOUTH	WEST
		Coefficient for calculation of average slab temperature		
Continuous running mode (24 h)	Floor and ceiling C2	-4.6816	-5.3696	-5.935
	Only ceiling C1	-6.3022	-7.2237	-7.7982
Intermittent running mode (8 h)	Floor and ceiling I2	-5.5273	-6.1701	-6.7323
	Only ceiling I1	-7.2853	-7.8562	-8.5791

Table 2 - Constant internal heat gains from 8:00 to 12:00 and from 14:00 to 18:00 (two peaks)

	Kind of floor	Exposure of the room		
		EAST	SOUTH	WEST
		Coefficient for calculation of average slab temperature		
Continuous running mode (24 h)	Floor and ceiling	-6.279	-7.1094	-7.3681
	Only ceiling	-7.9663	-8.7989	-8.7455
Intermittent running mode (8 h)	Floor and ceiling	-8.1474	-8.758	-9.3264
	Only ceiling	-10.029	-10.685	-10.967

Once θ_{comfort} is defined, the tables can be summarized by diagrams. For instance, if θ_{comfort} = 26 °C, the diagram for constant internal heat gains from 8:00 to 18:00 is given in Figure 9.



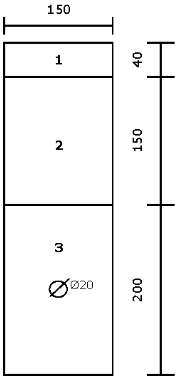
Key:

X-axis specific daily energy (kWh/m^2 per day)
Y-axis average slab temperature
coding of lines:
operation condition of the circuit (C = continuous, I = intermittent, 8 h)
number of active surfaces (1 or 2)
exposure of the room (E = East, S = South, W = West)

Figure 9 – Diagram for determining the average slab temperature in the case of constant internal heat gains during the day

Calculation example

- Q: 0,6 kWh/m^2 per day; shape of thermal loads: 2 peaks
- $\theta_{comfort}$: 26 °C
- Exposure of the room: SOUTH
- Kind of floor:



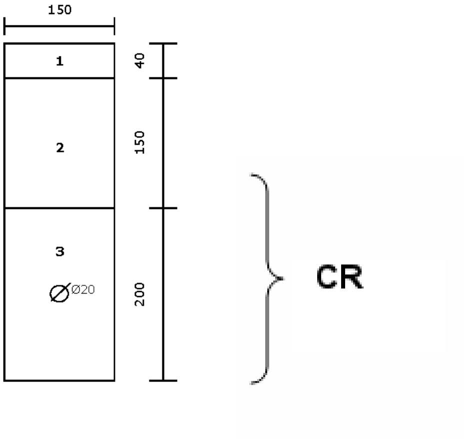
where:

1 = wood

2 = air

3 = reinforced concrete

- h: 8h
- R_{int}:



where:

CR = conductive region

If λ of the conductive region = 1,9 W/(m K), then

$R_{up} = R_{down}$ = 0,1/1,9 = 0,053 m^2K/W and R_{int} = 0,013 m^2K/W

- $\theta_s = 26 - 10{,}685 \cdot 0{,}6 = 19{,}6\ °C$
- R_t: 0,07 m^2K/W
- $\theta_w = 19{,}6 - \dfrac{0{,}6 \cdot (0{,}013 + 0{,}07) \cdot 1000}{8} = 13{,}38 °C$

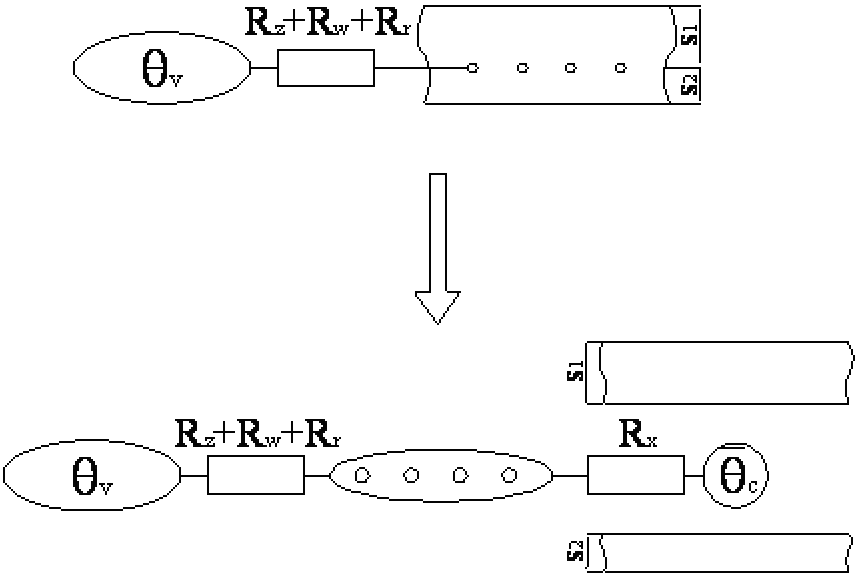
7.4 Simplified model based on finite difference method (FDM)

7.4.1 Cooling system

The limited power of the cooling system shall be taken into account. In fact, this implies that it is not possible to maintain a constant supply water temperature, since it depends on the amount of heat flux previously exchanged with the slab and on the maximum power of the chiller. A new inlet water temperature after each time step is calculated by taking into account the heat fluxes at the end of the previous time step.

7.4.2 Hydraulic circuit

The Resistance Method, as detailed in Annex B, is applied. It sets up a straightforward relation, expressed in terms of resistances, between the inlet water temperature and the average temperature at the pipes plane, $\bar{\theta}_c$. For this purpose, the slab may be split into two smaller slabs, i.e. the upper slab (which is above the pipes plane) and the lower slab (which is below the pipes plane) are considered separately (see Figure 10).



Key

θ_v	inlet water temperature
R_z	thermal resistance between the inlet water temperature and the supply water temperature along the pipe/circuit length
R_w	thermal resistance between the supply water temperature in the pipe and the internal surface temperature of the pipe wall
R_r	thermal resistance between the internal and external surface temperature of the pipe wall
R_x	thermal resistance between external surface temperature of the pipe wall and average temperature at the pipes plane

Figure 10 – Concept of the Resistance Method

7.4.3 Slab

The Resistance Method allows splitting of the slab into two parts, which are analyzed through an explicit finite difference method.

7.4.4 Room

An air node is taken into account coupled with the upward and downward surface of the slab and with a fictitious wall-node, via three resistances. Besides, the two surfaces of the slab are coupled together via a resistance taking into account the radiation exchange between them, and each slab surface is connected through a resistance to the wall-node (see Figure 11, 12 and 13).

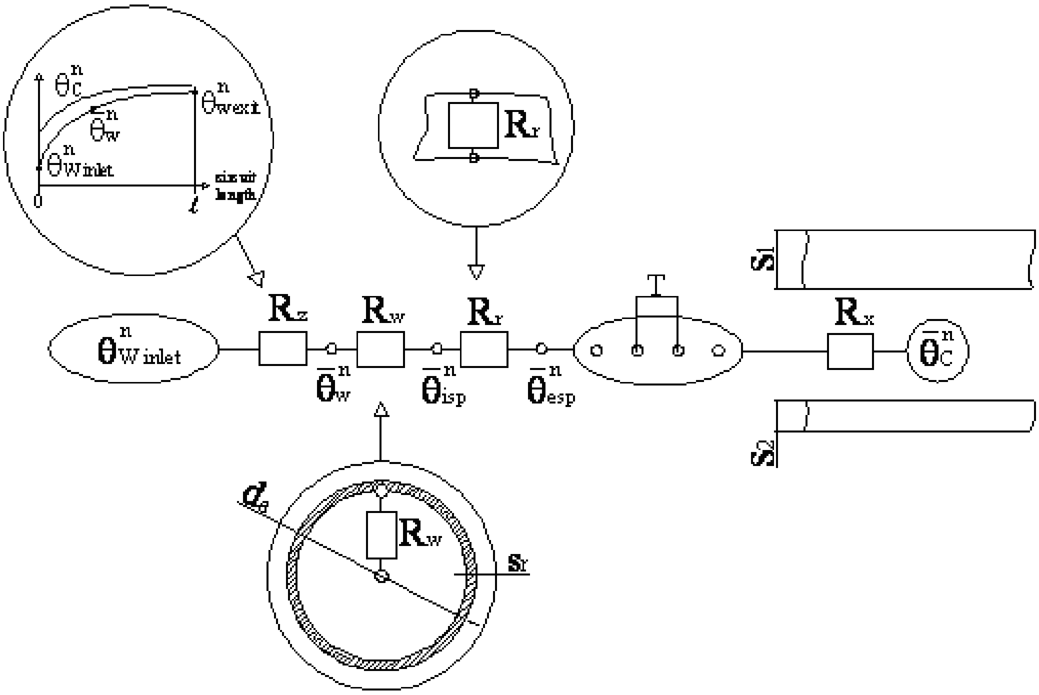
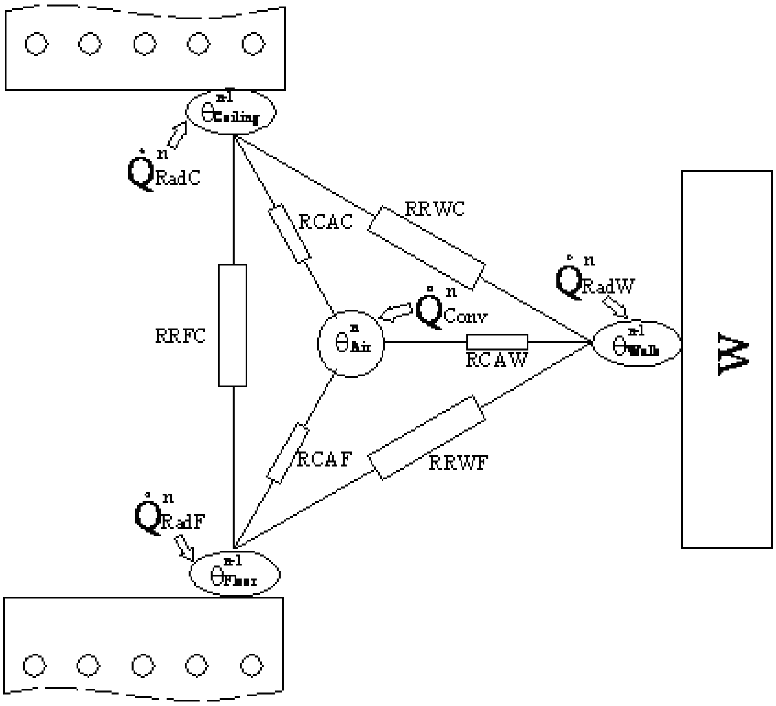


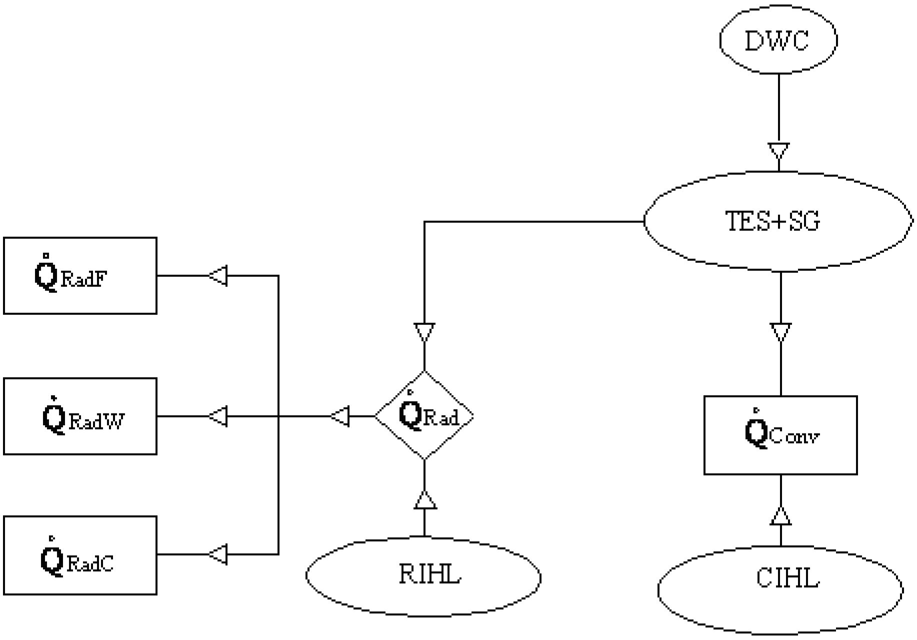
Figure 11 – General scheme of the Resistance Method



where:

W is the fictitious node describing the internal walls

Figure 12 – Scheme of the heat loads network



where:

DWC = design weather conditions

TES = transmission through the external surface

SG = solar gain

CIHL = convective internal heat loads

RIHL = radiant internal heat loads

Figure 13 – Heat loads involved acting on the room and how they take part in the calculations

7.4.5 Limits of the method

The following limitations shall be met:

- pipe spacing: from 0,15 to 0,3 m
- usual concrete slab structures have to be considered, λ = 1,15-2,0 W/(mK), 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 thermo-active system (see 7.5).

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 of 24 °C. The results of this calculation, to be taken into account as input for the present simplified model, are the solar gains and the heat fluxes into the room from the external surface.

7.5 Dynamic building simulations program

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 the upward and the 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.

8 Input for computer simulations of energy performance

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

For type E, F, and G systems according to prEN 15377-1, this resistance is directly calculated. Both the equivalent inward resistance and outward resistance are calculated.

For type A, B, C and D systems (according to prEN 15377-1 and prEN 1264-2 and -5), the equivalent resistances are calculated from the inward specific heat flow and the outward specific heat flow, taking into account the surface resistance according to:

$$R_x = \Delta\theta / q_x - 1/h_t \qquad \text{Km}^2/\text{W}$$

where:

R_x equivalent resistance, inward (x=i) or outward (x=u), Km²/W

$\Delta\theta$ heating/cooling medium temperature difference, K

q_x specific heat flow, inward (x=i) or outward (x=u), W/m²

h_t surface heat transfer coefficient, W/Km²

Annex A
(informative)

Simplified diagrams

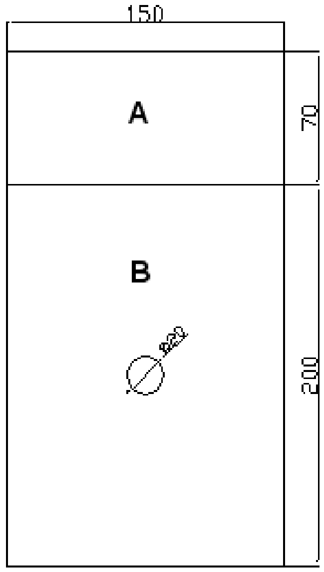
Based on the simplified calculation method in 7.3, the following diagrams for design of a TABS have been made. The diagrams in Figure A.2 show an example of the relation between internal heat gains, water supply temperature, heat transfer on the room side, hours of operation and heat transfer on the water side. The diagrams correspond to a concrete slab shown in Figure A.1 with a solid concrete floor (thermal conductivity 1,2 W/mK), pipe spacing of 0,15 m and a permissible room temperature range of 21 °C to 26 °C.

The upper diagram shows on the y-axis the maximum permissible total heat gain in the space (internal gains plus solar gains) in W/m^2, and on the x-axis the required water supply temperature in °C. The lines in the diagram correspond to different hours of operation (8 h, 12 h, 24 h) and different maximum amounts of energy supplied in Wh/m^2 per day.

The lower diagram shows the cooling power in W/m^2 required on the water side (for dimensioning of the chiller) for thermo-active slabs as a function of supply water temperature and operation time. Further, the amount of energy rejected is indicated in Wh/m^2 per day.

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 appr. 460 Wh/m^2 per day. The required cooling power on the water side is by 8 h operation 58 W/m^2 and by 24 h operation only 20 W/m^2. Thus, by 24 h operation, the size of the chiller can be reduced significantly.

dimensions in millimetres

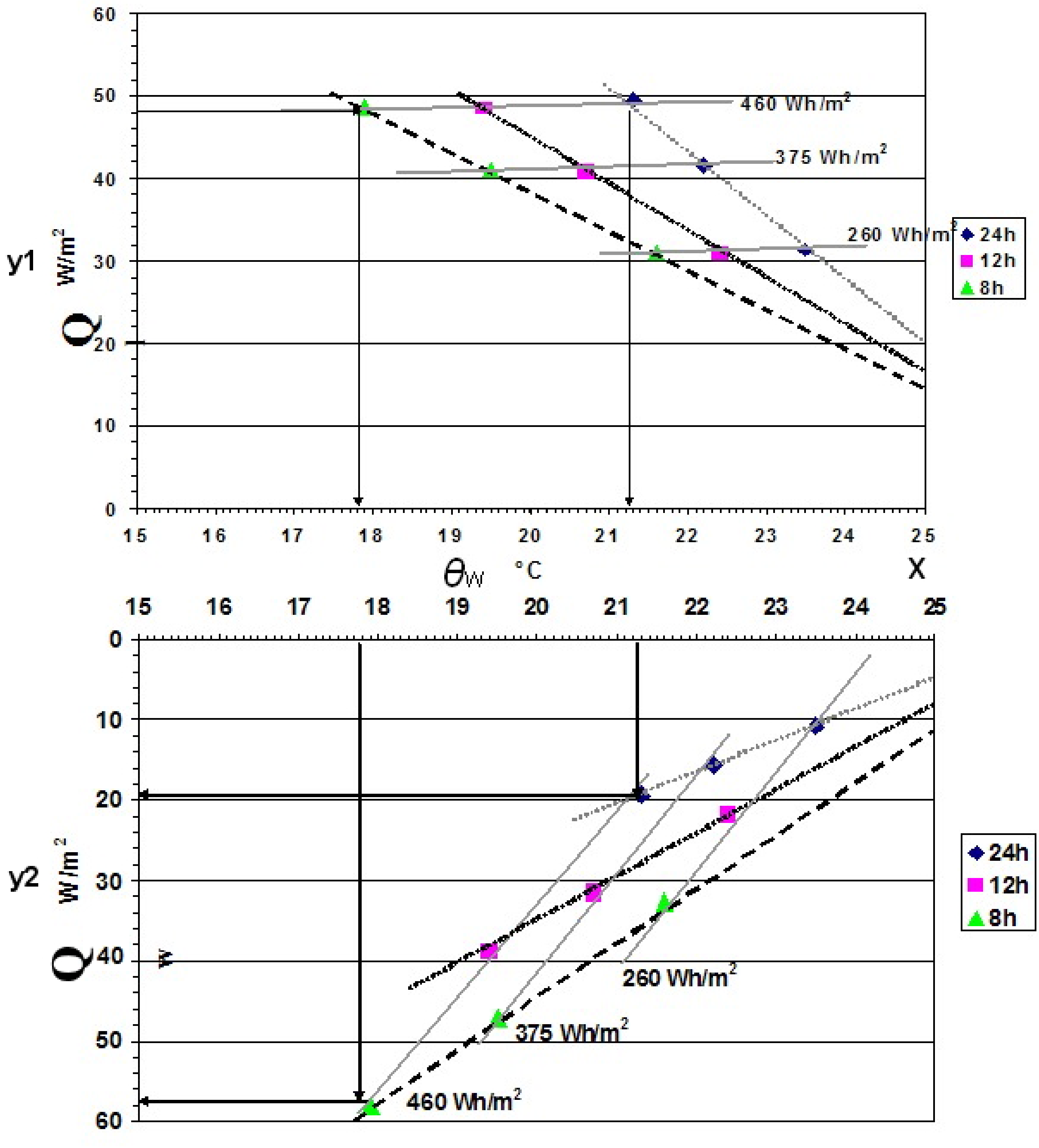


Key

A Concrete

B Reinforced concrete

Figure A.1 – Slab used in the simplified calculations



Key

X-axis	supply water temperature θ_w
y1	cooling load, *Q*
y2	required energy removal on the water side
Color and shape coded lines	corresponding to system running hours as indicated
Lines marked xxx Wh/m^2	indicating the total removed energy during the time of operation

Figure A.2 – Simple diagram for design of a TABS

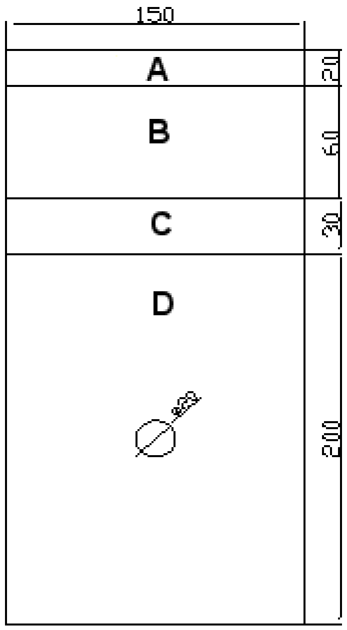
Based on the simplified calculation method in 7.3, the following diagrams for design of a TABS have been made. The diagrams in Figure A.4 show an example of the relation between internal heat gains, water supply temperature, heat transfer on the room side, hours of operation and heat transfer on the water side. The diagrams correspond to a concrete slab shown in Figure A.3 with a solid concrete floor (thermal conductivity 1,2 W/mK), pipe spacing of 0,15 m and a permissible room temperature range of 21 °C to 26 °C.

The upper diagram shows on the y-axis the maximum permissible total heat gain in the space (internal gains plus solar gains) in W/m^2, and on the x-axis the required water supply temperature in °C. The lines in the diagram correspond to different hours of operation (8 h, 12 h, 24 h) and different maximum amounts of energy supplied in Wh/m^2 per day.

The lower diagram shows the cooling power in W/m^2 required on the water side (for dimensioning of the chiller) for thermo-active slabs as a function of supply water temperature and operation time. Further, the amount of energy rejected is indicated in Wh/m^2 per day.

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 appr. 460 Wh/m^2 per day. The required cooling power on the water side is by 8 h operation 58 W/m^2 and by 24 h operation only 20 W/m^2. Thus, by 24 h operation, the size of the chiller can be reduced significantly.

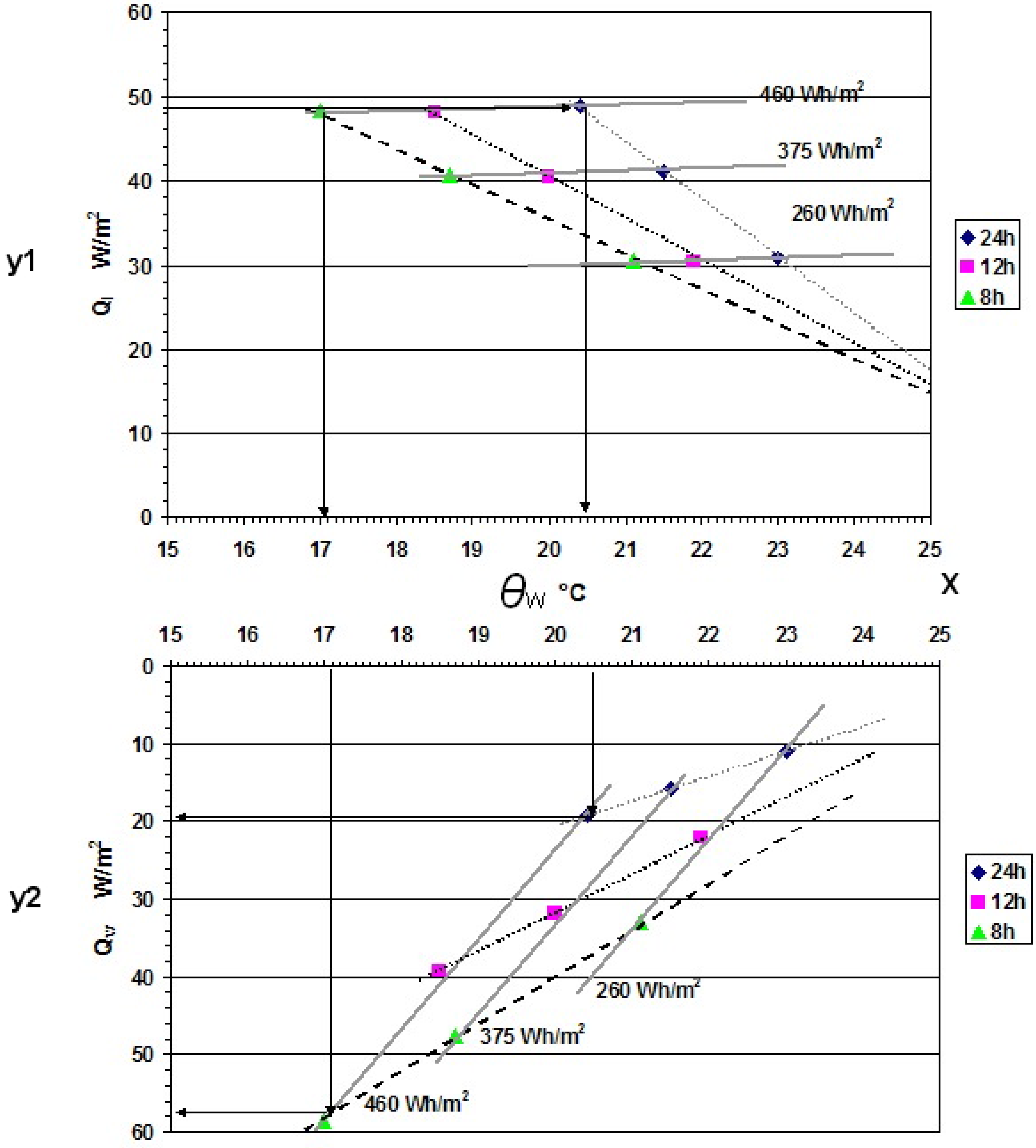
Dimensions in millimetres



Key

A Wood
B Concrete
C Fibreglass
D Reinforced concrete

Figure A.3 – Slab used in the simplified calculations



Key

X-axis	supply water temperature θ_w
y1	cooling load, Q
y2	required energy removal on the water side
Color and shape coded lines	corresponding to system running hours as indicated
Lines marked xxx Wh/m²	indicating the total removed energy during the time of operation

Figure A.4 – Simple diagram for design of a TABS

Annex B
(normative)

Calculation method

B.1 Pipes level

R_t is the total thermal resistance (m^{2}K)/W between the inlet water temperature and the average temperature at the pipes plane, determined by the Resistance Method. R_t can be calculated by:

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

where:

$$R_z = \frac{1}{2 \cdot \dot{m}_{H,sp} \cdot c_w} \qquad R_w = \frac{T^{0.13}}{8 \cdot \pi} \left(\frac{d_a - 2 \cdot s_r}{\dot{m}_{H,sp} \cdot L_R} \right)^{0.87}$$

$$R_r = \frac{T \cdot \ln\left(\frac{d_a}{d_a - 2 \cdot s_r} \right)}{2 \cdot \pi \cdot \lambda_r} \qquad R_x = \frac{T \cdot \ln\left(\frac{T}{\pi \cdot d_a} \right)}{2 \cdot \pi \cdot \lambda_r}$$

Two conditions shall be fulfilled for application of these equations:

— equation for R_x is valid only if $s_1 / T > 0{,}3$, $s_2 / T > 0{,}3$ and $d_a / T < 0{,}2$

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

If both conditions are fulfilled, Equation (B.1) can be applied.

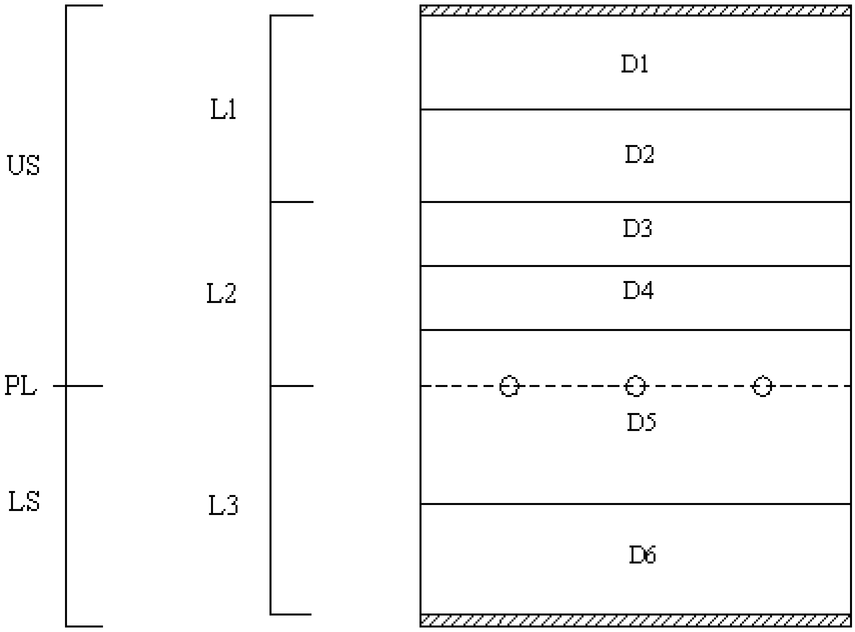
The machine model is expressed in an explicit way, so the inequality $R_t \cdot \dot{m}_{H,sp} \cdot c_w > 1$ shall be fulfilled in order to avoid calculations instability.

B.2 Subdivision of the slab

The slab is composed by J_1 material layers constituting the upper part of the slab, total thickness s_1, and J_2 material layers constituting the lower part of the slab, total thickness s_2. As a consequence, $J = J_1 + J_2$ sets of material layer thickness (δ_j) and physical properties (ρ_j, c_j, λ_j) shall be known. For geometrical consistency:

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

For the calculations, each material layer is subdivided into a number of partition layers. For each material layer, the number of partition layers, m_j, into which it is subdivided for the calculations, shall be decided.



Key

US	upper part of the slab	L	material layer
PL	pipes level	D	partition layer
LS	lower part of the slab		

Figure B.1 – Example of subdivision of the slab

Each partition layer inherits the physical properties from the material layer to which it belongs. Thus, if the k-th partition layer belongs to the j-th material layer, then $\lambda_{D,k} = \lambda_j$, $\rho_{D,k} = \rho_j$ and $c_{D,k} = c_j$.

The partition layers are used as thermal nodes in this method. The heat fluxes and temperatures pertaining to the partition layers are calculated for studying the capability of the system. In order to perform such calculations, each partition layer is characterized by four main physical values:

- thermal inertia $C_{D,k}$, which is calculated by taking into account the thickness of the partition layer $\tau_{D,k} = \frac{\delta_j}{m_j}$:

$$C_{D,k} = \rho_{D,k} \cdot c_{D,k} \cdot \tau_{D,k} = \rho_j \cdot c_j \cdot \frac{\delta_j}{m_j} \qquad \text{(B.2)}$$

- thermal resistance $RU_{D,k}$, which connects the present partition layer with the boundary of the upper partition layer:

$$RU_{D,k} = \frac{\left(\frac{\tau_{D,k}}{2}\right)}{\lambda_{D,k}} = \frac{\delta_j}{2 \cdot m_j \cdot \lambda_j} \tag{B.3}$$

- thermal resistance $RL_{D,k}$, which connects the present partition layer with the boundary of the lower partition layer;

$$RL_{D,k} = RU_{D,k} = \frac{\left(\frac{\tau_{D,k}}{2}\right)}{\lambda_{D,k}} = \frac{\delta_j}{2 \cdot m_j \cdot \lambda_j} \tag{B.4}$$

- heat transfer coefficient $HC_{D,k}$ between the present partition layer and the circuit;

$$HC_{D,k} = \frac{1}{R_t}\text{, if the partition layer borders on the pipes level,} \tag{B.5}$$

otherwise $HC_{D,k} = 0$

As is seen, two partition layers border on the pipes level and, thus, they share the thermal resistance R_t, and it is not possible to determine the heat flux passing through R_t by means of a single division. In order to avoid this difficulty, the two partition layers bordering on the pipes level are joined together, and constitute one single partition layer in the calculations.

As a consequence, the number of partition layers involved in the calculations is one less than the sum of the partition layers of all the material layers of the slab. For clarity, this sum is termed i_L, thus $i_L = \sum_{i=1}^{J} m_j - 1$.

Where a mere resistance layer is present, only R_j shall be specified.

The partition layer crossing the pipes level is the i_P-th partition layer, where $i_P = \sum_{i=1}^{J_1} m_j$. The temperature of this partition layer is important for the connection between the slab and the circuit, as seen in B.1, where the pipes level temperature is termed $\overline{\theta}_C^n$. By definition, $\overline{\theta}_C^n = \theta_{I,i_P}^n$, thus only θ_{I,i_P}^n is used.

As a consequence, the slab of Figure B.1 can be converted into the following RC network:

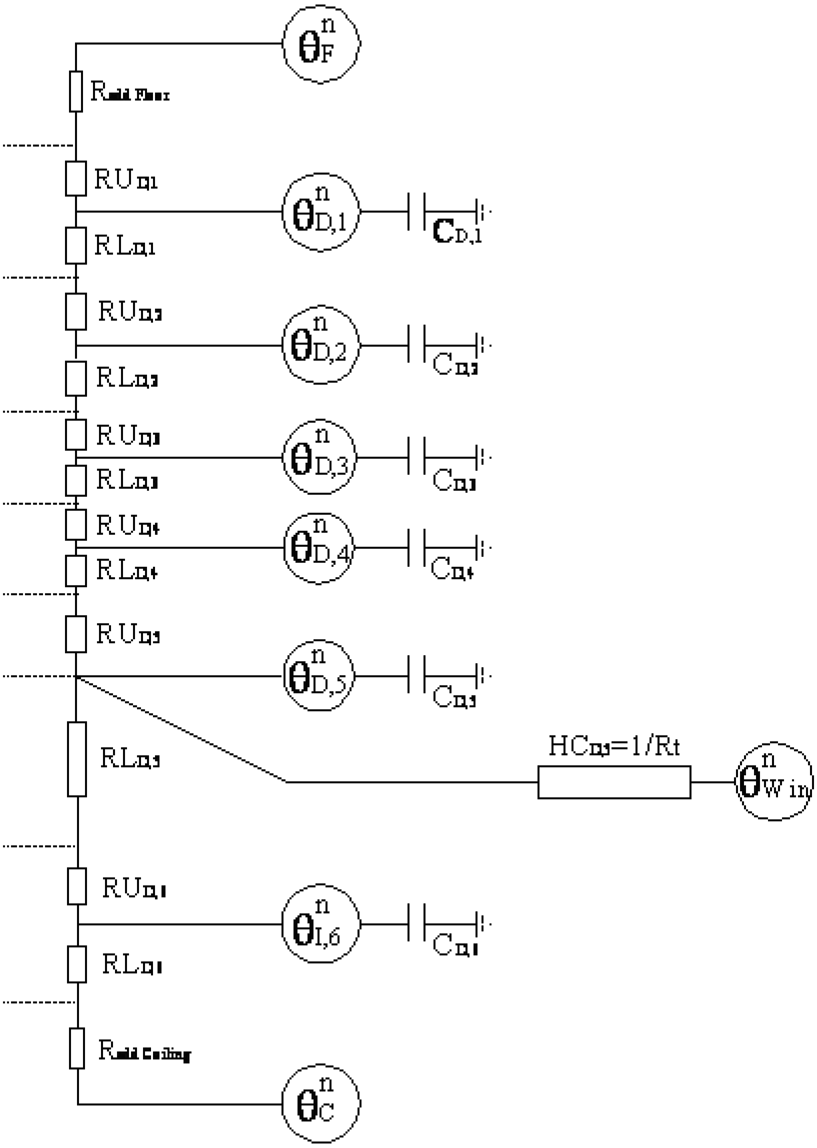


Figure B.2 – Equivalent RC network

Consequently, the following values characterizing the partition layers are defined:

Partition layer "i", with $1 < i < i_L$ and $i \neq i_P$:

$$C_{D,i} = \rho_j \cdot c_j \cdot \frac{\delta_j}{m_j}$$

$$RU_{D,i} = \frac{\delta_j}{2 \cdot m_j \cdot \lambda_j} + \frac{R_{j-1}}{2}$$ if D,i is the upper element of the j-th material layer and the (j-1)-th material layer is a mere resistance

$$RU_{D,i} = \frac{\delta_j}{2 \cdot m_j \cdot \lambda_j}$$

if D,i is neither the upper element nor the lower element of the j-th material layer, or if the (j-1)-th material layer is not a mere resistance

$$RL_{D,i} = \frac{\delta_j}{2 \cdot m_j \cdot \lambda_j} + \frac{R_{j+1}}{2}$$

if D,i is the lower element of the j-th material layer and the (j+1)-th material layer is a mere resistance

$$RL_{D,i} = \frac{\delta_j}{2 \cdot m_j \cdot \lambda_j}$$

if D,i is neither the upper element nor the lower element of the j-th material layer, or if the (j+1)-th material layer is not a mere resistance

$$HC_{D,i} = 0$$

Partition layer “i_P”:

$$C_{D,i_P} = \rho_{J_1} \cdot c_{J_1} \cdot \frac{\delta_{J_1}}{m_{J_1}} + \rho_{J_1+1} \cdot c_{J_1+1} \cdot \frac{\delta_{J_1+1}}{m_{J_1+1}}$$

$$RU_{D,i_P} = \frac{\delta_{J_1}}{2 \cdot m_{J_1} \cdot \lambda_{J_1}} + \frac{R_{J_1-1}}{2}$$

if D,i is the upper element of the J_1-th material layer and the (J_1-1)-th material layer is a mere resistance

$$RU_{D,i_P} = \frac{\delta_{J_1}}{m_{J_1} \cdot \lambda_{J_1}}$$

if D,i is neither the upper element nor the lower element of the J_1-th material layer, or if the (J_1-1)-th material layer is not a mere resistance

$$RL_{D,i_P} = \frac{\delta_{J_1+1}}{2 \cdot m_{J_1+1} \cdot \lambda_{J_1+1}} + \frac{R_{J_1+2}}{2}$$

if D,i is the lower element of the (J_1+1)-th material layer and the (J_1+2)-th material layer is a mere resistance

$$RL_{D,i_P} = \frac{\delta_{J_1+1}}{m_{J_1+1} \cdot \lambda_{J_1+1}}$$

if D,i is neither the upper element nor the lower element of the (J_1+1)-th material layer, or if the (J_1+2)-th material layer is not a mere resistance

$$HC_{D,i_P} = \frac{1}{R_t}$$

B.3 Choice of the calculation time step:

The calculation time step shall be chosen in order to avoid calculations instability. A safe value for the calculation time step is evaluated to be around 40 s.

B.4 Calculations for the generic n-th time step

The values of $\dot{Q}^n_{Sun}$, $\dot{Q}^n_{Transm}$, $\dot{Q}^n_{Air}$, $\dot{Q}^n_{IntRad}$ and $\dot{Q}^n_{IntConv}$ shall be known for the whole day. $\dot{Q}^n_{Sun}$ and $\dot{Q}^n_{Transm}$ 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 24 °C). $\dot{Q}^n_{IntRad}$, $\dot{Q}^n_{IntConv}$ and $\dot{Q}^n_{Air}$ depend on the people and the equipment in the room and on the possible air circuit, and are thus known.

For every time step, the running strategy of the circuit f_{rm}^{n} shall be decided before the simulation is started, and the supply water temperature θ_W^n is an input parameter 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.

For beginning of the simulation, initial values of temperatures of the slab, $\theta_{D,i}^0$ (with $1 \le i \le i_L$), temperature of the air, θ_{Air}^0 , temperature of the walls, θ_{Walls}^0 , supply water temperature, θ_W^0 , and outlet water temperature, $\theta_{W\,exit}^0$, shall be defined. These are only initial values and do not influence the subsequent results, as long as the simulation time is sufficiently long.

The following shortcuts are useful in the subsequent calculations:

$$RCAC = \frac{1}{h_{Air-Ceiling}} + R_{add\,Ceiling} + RL_{D,i_L}$$

$$RRWC = \frac{1}{h_{Ceiling-Walls}} + R_{add\,Ceiling} + RL_{D,i_L} + R_{Walls} \cdot \frac{A_{Floor}}{A_{Walls}}$$

$$RRFC = \frac{1}{h_{Floor-Ceiling}} + R_{add\,Floor} + R_{add\,Ceiling} + RL_{D,i_L} + RU_{D,1}$$

$$RCAW = \frac{1}{h_{Air-Walls}} + R_{Walls}$$

$$RRWF = \frac{1}{h_{Floor-Walls}} + R_{add\,Floor} + RU_{D,1} + R_{Walls} \cdot \frac{A_{Floor}}{A_{Walls}}$$

$$RCAF = \frac{1}{h_{Air-Floor}} + R_{add\,Floor} + RU_{D,1}$$

$where:$

$$h_{Floor-Walls} = h_{Ceiling-Walls} = 4 \cdot \sigma \cdot 300^3 \cdot F_{v\,Floor-Walls}$$

$$h_{Floor-Ceiling} = 4 \cdot \sigma \cdot 300^3 \cdot F_{v\,Floor-Ceiling}$$

$$F_{v\,Floor-Walls} = 1 - F_{v\,Floor-Ext\,Wall} - F_{v\,Floor-Ceiling}$$

$$\sigma = \text{Stefan - Bolzmanns constant} \;\; 5.67 \cdot 10^{-8} \;\; W/(m^2 K^4)$$

For the n-th time step, the following calculations shall be executed:

- Determination of supply water temperature:

$$\theta_W^n = \theta_{W\,exit}^{n-1} + \frac{P_W^{Max}}{\dot{m}_{H,sp} \cdot c_w \cdot A_{Floor}} \quad , \; if \;\; \theta_{W\,exit}^{n-1} + \frac{P_W^{Max}}{\dot{m}_{H,sp} \cdot c_w \cdot A_{Floor}} > \theta_W^{\lim}$$

$$\theta_W^n = \theta_W^{\lim} \quad , \; if \; \theta_{W\,exit}^{n-1} + \frac{P_W^{Max}}{\dot{m}_{H,sp} \cdot c_w \cdot A_{Floor}} < \theta_W^{\lim}$$

- Calculation of the heat loads acting towards the room:

$$\dot{Q}_{Conv}^n = 0.15 \cdot \dot{Q}_{Transm}^n + \dot{Q}_{IntConv}^n$$

$$\dot{Q}_{Rad}^n = 0.85 \cdot \dot{Q}_{Transm}^n + \dot{Q}_{Sun}^n + \dot{Q}_{IntRad}^n$$

- Calculation of the air temperature necessary in order to transfer all convective gains to the surfaces surrounding the room:

$$\theta_{Air}^n = \frac{\dot{Q}_{Conv}^n - \dot{Q}_{Air}^n + \frac{A_{Walls}}{RCAW} \cdot \theta_{Walls}^{n-1} + \frac{A_{Floor}}{RCAF} \cdot \theta_{D,1}^{n-1} + \frac{A_{Floor}}{RCAC} \cdot \theta_{D,i_L}^{n-1}}{\frac{A_{Walls}}{RCAW} + \frac{A_{Floor}}{RCAF} + \frac{A_{Floor}}{RCAC}}$$

- Calculation of the heat loads acting on the surfaces:

$$\dot{Q}_{RadW}^n = \dot{Q}_{Rad}^n \cdot \frac{A_{Walls}}{2 \cdot A_{Floor} + A_{Walls}}$$

$$\dot{Q}_{RadF}^n = \dot{Q}_{Rad}^n \cdot \frac{A_{Floor}}{2 \cdot A_{Floor} + A_{Walls}}$$

$$\dot{Q}_{RadC}^n = \dot{Q}_{Rad}^n \cdot \frac{A_{Floor}}{2 \cdot A_{Floor} + A_{Walls}}$$

$$\dot{Q}_{RadWF}^n = \frac{\left(\theta_{Walls}^{n-1} - \theta_{D,1}^{n-1}\right)}{RRWF} \cdot A_{Floor}$$

$$\dot{Q}_{RadWC}^n = \frac{\left(\theta_{Walls}^{n-1} - \theta_{D,i_L}^{n-1}\right)}{RRWC} \cdot A_{Floor}$$

$$\dot{Q}_{RadFC}^n = \frac{\left(\theta_{D,1}^{n-1} - \theta_{D,i_L}^{n-1}\right)}{RRFC} \cdot A_{Floor}$$

$$\dot{Q}_{ConvW}^n = \frac{\left(\theta_{Air}^{n} - \theta_{Walls}^{n-1}\right)}{RCAW} \cdot A_{Walls}$$

$$\dot{Q}_{ConvF}^n = \frac{\left(\theta_{Air}^{n} - \theta_{D,1}^{n-1}\right)}{RCAF} \cdot A_{Floor}$$

$$\dot{Q}_{ConvC}^n = \frac{\left(\theta_{Air}^{n} - \theta_{D,i_L}^{n-1}\right)}{RCAC} \cdot A_{Floor}$$

$$\dot{q}_{OnFloor}^n = \frac{\dot{Q}_{RadF}^n + \dot{Q}_{RadWF}^n - \dot{Q}_{RadFC}^n + \dot{Q}_{ConvF}^n}{A_{Floor}}$$

$$\dot{q}_{OnCeiling}^n = \frac{\dot{Q}_{RadC}^n + \dot{Q}_{RadWC}^n + \dot{Q}_{RadFC}^n + \dot{Q}_{ConvC}^n}{A_{Floor}}$$

$$\dot{q}_{OnWalls}^n = \frac{\dot{Q}_{RadW}^n - \dot{Q}_{RadWF}^n - \dot{Q}_{RadWC}^n + \dot{Q}_{ConvW}^n}{A_{walls}}$$

- Calculation of the temperature of the walls and the temperatures of the slab:

$$\theta^n_{Walls} = \frac{\left(\dot{Q}^n_{RadW} - \dot{Q}^n_{RadWF} - \dot{Q}^n_{RadWC} + \dot{Q}^n_{ConvW}\right)\cdot \Delta t}{C_{Walls}\cdot A_{Walls}} + \theta^{n-1}_{Walls}$$

$$\theta^n_{D,1} = \frac{\left(\dot{q}^n_{OnFloor} + \frac{\left(\theta^{n-1}_{D,2} - \theta^{n-1}_{D,1}\right)}{RL_{D,1} + RU_{D,2}}\right)\cdot \Delta t}{C_{D,1}} + \theta^{n-1}_{D,1}$$

$$\theta^n_{D,i} = \frac{\left(\frac{\left(\theta^{n-1}_{D,i-1} - \theta^{n-1}_{D,i}\right)}{RL_{D,i-1} + RU_{D,i}} + \frac{\left(\theta^{n-1}_{D,i+1} - \theta^{n-1}_{D,i}\right)}{RL_{D,i} + RU_{D,i+1}} + f^n_{rm}\left(\theta^n_W - \theta^{n-1}_{D,i}\right)\cdot HC_{D,i}\right)\cdot \Delta t}{C_{I,i}} + \theta^{n-1}_{D,i} \quad \text{with} \quad 2 \le i \le i_L - 1$$

$$\theta^n_{D,i_L} = \frac{\left(\dot{q}^n_{OnCeiling} + \frac{\left(\theta^{n-1}_{D,i_L-1} - \theta^{n-1}_{D,i_L}\right)}{RL_{D,i_L-1} + RU_{D,i_L}}\right)\cdot \Delta t}{C_{D,i_L}} + \theta^{n-1}_{D,i_L}$$

$$\theta^n_F = \dot{q}^n_{OnFloor}\cdot\left(R_{add\,Floor} + RU_{D,1}\right) + \theta^n_{D,1}$$

$$\theta^n_C = \dot{q}^n_{OnCeiling}\cdot\left(R_{add\,Ceiling} + RL_{D,i_L-1}\right) + \theta^n_{D,i_L}$$

$$\theta^n_W = \dot{q}^n_{OnWalls}\cdot\left(R_{Walls}\right) + \theta^n_{Walls}$$

- Calculation of outlet water temperature:

$$\theta^n_{W\,exit} = \theta^n_W - \frac{\left(\theta^n_W - \theta^{n-1}_{D,i_P}\right)}{R_t}\cdot \dot{m}_{H,sp}\cdot c_w\cdot A_{Floor} \;,\; if\ f^n_{rm} = 1$$

$$\theta^n_{W\,exit} = \theta^n_{D,i_P} \;,\; if\ f^n_{rm} = 0$$

- Calculation of operative temperature:

$$\theta^n_{Op} = \frac{\theta^n_{Air} + \frac{\theta^n_F\cdot A_{Floor} + \theta^n_C\cdot A_{Floor} + \theta^n_W\cdot A_{Walls}}{\left(2\cdot A_{Floor} + A_{Walls}\right)}}{2}$$

B.5 Sizing of the system

The allowed range for the operative temperature of the room is 20 °C to 25,5 °C, as the program underestimates the temperature of the room. If the operative temperature is always in this range, 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:

$\dot{m}_{H,sp}$	10 kg/(m^2 s)	Input
c_w	4187 J/(kg K)	Input
T	0,2 m	Input
d_a	0,025 m	Input
s_r	0,0025 m	Input
λ_r	0,35 W/(m K)	Input
A_{Floor}	15 m^2	Input
L_R	15/0,2 = 75 m	Result
R_t	0,073 m^{2}K/W	Result
P_W^{Max}	1000 W	Input
θ_w^0	19 °C	Input
θ_w^{lim}	19 °C	Input

A_{Walls}	33 m^2	Input
$F_{v\ Floor\text{-}Ext\ Wall}$	0,23	Input
$F_{v\ Floor\text{-}Ceiling}$	0,3	Input
$F_{v\ Floor\text{-}Walls}$	0,47	Result
$R_{add\ Floor}$	0,1 (m^2 K)/W	Input
$R_{add\ Ceiling}$	0 (m^2 K)/W	Input
R_{Walls}	0,05 (m^2 K)/W	Input
$h_{Air\text{-}Floor}$	1,5 W/(m^2 K)	Input
$h_{Air\text{-}Ceiling}$	5,5 W/(m^2 K)	Input
$h_{Air\text{-}Walls}$	2,5 W/(m^2 K)	Input

$h_{Floor\text{-}Walls}$	2,88 W/(m^2 K)	Result
$h_{Ceiling\text{-}Walls}$	2,88 W/(m^2 K)	Result
$h_{Floor\text{-}Ceiling}$	1,84 W/(m^2 K)	Result
C_{Walls}	10600 J/(m^2 K)	Input
Δt	60 s	Input
$T_{comfort}$	25,5 °C	Input
$\dot{Q}^n_{Sun}$	300 W	Input
$\dot{Q}^n_{Transm}$	90 W	Input
$\dot{Q}^n_{Air}$	0 W	Input
$\dot{Q}^n_{IntRad}$	400 W	Input
$\dot{Q}^n_{IntConv}$	600 W	Input
f^n_{rm}	1	Input
s_1	0,14 m	Input
s_2	0,1 m	Input
J_1	3	Input
J_2	1	Input
ρ_1	700 kg/m^3	Input
c_1	2300 J/(kg K)	Input
λ_1	0,17 W/(m K)	Input
δ_1	0,04 m	Input
m_1	2	Input
R_1	0 (m^2 K)/W	Input
ρ_2	0 kg/m^3	Input
c_2	0 J/(kg K)	Input
λ_2	0 W/(m K)	Input
δ_2	0 m	Input
m_2	0	Input

R_2	0,18 (m^2 K)/W	Input
ρ_3	2000 kg/m^3	Input
c_3	880 J/(kg K)	Input
λ_3	1,9 W/(m K)	Input
δ_3	0,1 m	Input
m_3	3	Input
R_3	0 (m^2 K)/W	Input
ρ_4	2000 kg/m^3	Input
c_4	880 J/(kg K)	Input
λ_4	1,9 W/(m K)	Input
δ_4	0,1 m	Input
m_4	3	Input
R_4	0 (m^2 K)/W	Input
θ_{Walls}^{n-1}	24 °C	Result of calculations at the previous time step
$\theta_{D,1}^{n-1}$	22,5 °C	Result of calculations at the previous time step
$\theta_{D,2}^{n-1}$	22,3 °C	Result of calculations at the previous time step
$\theta_{D,3}^{n-1}$	21,5 °C	Result of calculations at the previous time step
$\theta_{D,4}^{n-1}$	21,4 °C	Result of calculations at the previous time step
$\theta_{D,5}^{n-1}$	21,3 °C	Result of calculations at the previous time step
$\theta_{D,6}^{n-1}$	21,4 °C	Result of calculations at the previous time step
$\theta_{D,7}^{n-1}$	21,5 °C	Result of calculations at the previous time step
θ_{Walls}^{n}	24,074 °C	Result
$\theta_{D,1}^{n}$	22,521 °C	Result
$\theta_{D,2}^{n}$	22,297 °C	Result

$\theta^{n}_{D,3}$	21,5027 °C	Result
$\theta^{n}_{D,4}$	21,4019 °C	Result
$\theta^{n}_{D,5}$	21,287 °C	Result
$\theta^{n}_{D,6}$	21,4019 °C	Result
$\theta^{n}_{D,7}$	21,54 °C	Result
θ^{n}_{F}	24,58 °C	Result
θ^{n}_{C}	21,94 °C	Result
θ^{n}_{W}	24,73 °C	Result

Annex D
(informative)

Computer program

```
Program TC228_R5_RES_EL_OK

USE DFLIB

implicit none





! Definition of the Types in the main


Type      Layer                                 ! Definition of each layer

          Character*1    Kind                   ! "M" if it is a material layer; "R" if it is a pure resistance
                                                layer; Every "R" layer must be bounded by two "M"
                                                layers

          Integer        NElements              ! Number of parts into which the layer must be divided
                                                in order to perform the calculations

          Real           Thickness              ! Thickness of the layer  m

          Real           Lambda                 ! Conductivity of the material constituting the layer
                                                W/(m K)

          Real           SpecHeat               ! Specific heat of the material constituting the layer
                                                J/(kg K)

          Real           Rho                    ! Density of the material constituting the layer  Kg/m3

          Real           Resistance             ! Resistance of the layer: to be compiled only if
                                                Kind="R", otherwise its value is 0  (m2 K)/W

          Integer        InitialElement         ! Upper element belonging to the layer

          Integer        FinalElement           ! Lower element belonging to the layer

          Real           ElThickness            ! Thickness of each element of the layer  m

End Type  Layer
```

```
Type        El                                  ! Definition of each element constituting the slab

            Real        Capacity                ! Thermal capacity assigned to the present element  J/K

            Real        ResistanceUp            ! Resistance connecting the present element with the
                                                upper one  (m2 K)/W

            Real        ResistanceDown          ! Resistance connecting the present element with the
                                                lower one  (m2 K)/W

            Integer     ExtH                    ! Possible connection of the present element with the
                                                circuit  (m2 K)/W : 1 if the present element is at the
                                                pipes level, otherwise 0

End Type    El



Type        HeatLoadsAndCircuit                 ! Definition of the boundary conditions for loads, water
                                                temperature and running mode

            Integer     Time                    ! Final time of the present time step  s

            Integer     RunningMode             ! Hydronic circuit running mode in the present time step
                                                1/0

            Real        Twater                  ! Inlet water temperature in the present time step  °C

            Real        RadiantHeatFlux         ! Radiant heat flux imposed in the room in the present
                                                time step  W

            Real        ConvectiveHeatFlux      ! Convective heat flux imposed in the room in the
                                                present time step  W

            Real        QAir                    ! Convective heat flux extracted by the primary air
                                                circuit  W

EndType HeatLoadsAndCircuit



! Definition of the variables involved by the main


Type        (Layer)::   Layers(1:20)            ! Maximum number of layers constituting the slab = 20

Type        (El)::      Element(1:50)           ! Maximum number of interfaces dividing the slab = 50

Type (HeatLoadsAndCircuit):: Boundary(0:320000) ! Maximum number of time steps for input of heat loads
                                                and other boundary conditions = 320000
```

```
Real       FvFloorToCeiling

Real       hFloorToCeiling             ! Radiant coefficient Floor-Ceiling  W/(m2 K)

Real       hAirToFloor                 ! Convective coefficient Air-Floor  W/(m2 K)

Real       hAirToCeiling               ! Convective coefficient Air-Ceiling  W/(m2 K)

Real       UpperResistance             ! Additional resistance on the floor (such as carpets or
                                       moquette)  (m2 K)/W

Real       LowerResistance             ! Additional resistance covering the ceiling (such as
                                       suspended ceiling)  (m2 K)/W

Real       WallsResistance             ! Resistance related to the walls node

Real       Rtot                        ! Resistance concerning the circuit and connecting the
                                       average pipes level temperature with the inlet water
                                       temperature  (m2 K)/W

Real       hAirToWalls                 ! Convective coefficient Air-Walls  W/(m2 K)

Real       hSlabToWalls                ! Radiant coefficient Walls-Slab  W/(m2 K)

Real       FvSlabToExtWall             ! Radiant coefficient Walls-Slab  W/(m2 K)

Integer    NLayersUp                   ! Number of layers constituting the upper part of the
                                       slab

Integer    NLayersDown                 ! Number of layers constituting the lower part of the slab

Integer    UpperElement                ! Ordinal number characterizing the upper element:
                                       imposed value = 1

Integer    PipesLevelElement           ! Ordinal number characterizing the pipes level element

Integer    LowerElement                ! Ordinal number characterizing the lower element

Real       FloorArea                   ! Area of the floor  m2

Real       AreaWalls                   ! Area of the walls  m2

Integer    TimeStep                    ! Time step for the imposition of boundary conditions  s

Real       WallsInertia                ! Walls thermal inertia per square meter  J/(m2 K)

Integer NSteps                         ! Number of time steps used for the input of boundary
                                       conditions

Integer    NTimes                      ! Number of repetitions of the input loads cycle

Integer    TimeCycle                   ! Time of a single input loads cycle  s

Integer    TotalTime                   ! Total time of the performed simulation  s

Real       Temperatures(1:50,0:640000) ! Temperatures of the elements constituting the slab  °C
                                       (maximum number of calculation time steps = 640000)
```

```
Real          Tair(0:640000)                    ! Temperatures of the room air  °C  (maximum number
                                                of calculation time steps = 640000)

Real          TWalls(0:640000)                  ! Temperatures of the walls  °C  (maximum number of
                                                calculation time steps = 640000)

Real          qsOnFloor(0:640000)               ! Global heat fluxes acting onto the floor  W/m2
                                                (maximum number of calculation time steps = 640000)

Real          qsOnCeiling(0:640000)             ! Global heat fluxes acting onto the ceiling  W/m2
                                                (maximum number of calculation time steps = 640000)

Real          qsOnWalls(0:640000)               ! Heat fluxes acting onto the walls  W/m2  (maximum
                                                number of calculation time steps = 640000)

Real          qsToCircuit(0:640000)             ! Heat fluxes extracted by the circuit  W/m2  (maximum
                                                number of calculation time steps = 640000)

Real          TOp(0:640000)                     ! Operative temperatures in the room (maximum
                                                number of calculation time steps = 640000)

Integer CalcTimeStep                            ! Calculation time step  s

Integer NCalcTimeSteps                          ! Number of calculation steps executed in the whole
                                                simulation

Real          TimeInHours                       ! Support value for the output of the results  h

Real          TsurfW(0:640000)

Real          TsurfF(0:640000)

Real          TsurfC(0:640000)

CHARACTER*32                OutputFile



Integer i                                       ! Support counter

Integer j                                       ! Support counter

Integer Deleted                                 ! Support variable
```

```
! Main ______________________________________________________________________________

! Removal of the previous simulation output and creation of the new one (the output file name is ".ris")

! Formats for input and output commands

1 Format(x,f6.3,3x,f6.3,3x,f6.3,3x,f6.3,3x,f6.3,3x,f6.3,3x,f6.3,x,f6.3,x,f6.3)

2 Format(x,i2,3x,a1,3x,i2,3x,f6.4,3x,f6.4,3x,f7.2,3x,f7.2,3x,f7.4,3x,i2,3x,i2,3x,f6.4)

3 Format(x,i9,xx,f13.1,xx,f7.4,xx,f7.4,xx,i1)

4 Format(x,f9.3,x,i1,x,f4.1,x,f6.2,x,f6.2,x,f6.2)

5 Format(x,f9.3,x,f8.3,x,f8.3,x,f8.3,x,f8.3,x,f8.3,x,f8.3)

6 Format(x,f9.3,3x,f6.2,3x,f6.2,12x,f10.2,11x,f10.2)

7 Format(x,a6,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,
i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,i3,6x,a20)

8 Format(x,i3,6x,i3,6x, f4.1,6x, f4.1,6x,f10.1)

! Call of the three subroutines for reading data, creating interfaces and calculating the thermal behaviour of the room

Call ReadSlabAndLoads (hFloorToCeiling, hAirToFloor, hAirToCeiling, UpperResistance, LowerResistance, WallsResistance, Rtot, hAirToWalls, hSlabToWalls, NLayersUp, NLayersDown, Layers, UpperElement, PipesLevelElement, LowerElement, FloorArea, AreaWalls, TimeStep, WallsInertia, NSteps, NTimes, TimeCycle, TotalTime, Boundary, FvSlabToExtWall, FvFloorToCeiling, OutputFile, CalcTimeStep)

Deleted = DELFILESQQ (OutputFile)

Open(unit=2, file=OutputFile, status='new')

Call CreateInterfaces (UpperResistance, LowerResistance, NLayersUp, NLayersDown, Layers, UpperElement, PipesLevelElement, LowerElement, Element)

Call CreateTempAndFluxesTables (hFloorToCeiling, hAirToFloor, hAirToCeiling, UpperResistance, LowerResistance, WallsResistance, Rtot, hAirToWalls, hSlabToWalls, NLayersUp, NLayersDown, Element, UpperElement, PipesLevelElement, LowerElement, FloorArea, AreaWalls, TimeStep, WallsInertia, NSteps, NTimes, TimeCycle, TotalTime, Boundary, Temperatures, Tair, TWalls, QsOnFloor, QsOnCeiling, QsOnWalls, QsToCircuit, CalcTimeStep, NCalcTimeSteps, TOp, TsurfW, TsurfC, TSurfF)
```

```
! Output printing___________________________________________________________________________


! Initial data printing


write(2,*) 'hF2C    hA2F    hA2C     UpRes     LowRes     Rtot   hA2W  hW2S WallsResistance'

write(2,1) hFloorToCeiling, hAirToFloor, hAirToCeiling, UpperResistance, LowerResistance, Rtot, hAirToWalls,
hSlabToWalls, WallsResistance

write(2,*)

write(2,*) 'NLayUp        NLayDown     AFloor    AWalls    WallsInertia'

write(2,8) NLayersUp, NLayersDown, FloorArea, AreaWalls, WallsInertia

write(2,*)


! Main interfaces numbers and slab divisions printing


write(2,*) 'UpInterf       PLevelInterf     LowInterf'

write(2,*) UpperElement, PipesLevelElement, LowerElement

write(2,*)

write(2,*) 'NLay  Kind  NParts  LThick  LLamb  LSpecHeat  LRho  LRes  InSurf  FinSurf  ElThick'

do i=1,20

      write(2,2) i, Layers(i).Kind, Layers(i).NElements, Layers(i).Thickness, Layers(i).Lambda,
      Layers(i).SpecHeat, Layers(i).Rho, Layers(i).Resistance, Layers(i).InitialElement, Layers(i).FinalElement,
      Layers(i).ElThickness

enddo

write(2,*)

write(2,*) 'i IntCapacity  IntResUp IntResDown IntExtH'

do i=1,23

      write(2,3) i, Element(i).Capacity, Element(i).ResistanceUp, Element(i).ResistanceDown, Element(i).ExtH

enddo

write(2,*)
```

```
! Printing of the time values involved by the calculations


write(2,*) 'TimeStep    NSteps    NTimes  TimeCycle    TotalTime    NCalcTimeSteps'

write(2,*) TimeStep, NSteps, NTimes, TimeCycle, TotalTime, NCalcTimeSteps

write(2,*)


! Boundary loads printing


write(2,*) 'Time   Run  Twat  Rad   Conv  QAir'

do i=0,NSteps*NTimes

     IF (MOD(i*CalcTimeStep,600).eq.0) THEN

     TimeInHours=Boundary(i).Time/3600.0

     write(2,4) TimeInHours, Boundary(i).RunningMode, Boundary(i).Twater, Boundary(i).RadiantHeatFlux,
     Boundary(i).ConvectiveHeatFlux, Boundary(i).QAir

     ENDIF

enddo

write(2,*)


! Main temperatures printing


write(2,*) ' Time   TFloor    TCore    TCeiling    Tair    TOp     TWalls'

do i=0,NCalcTimeSteps

     IF (MOD(i*CalcTimeStep,600).eq.0) THEN

     TimeInHours=i*CalcTimeStep/3600.0

     write(2,5)      TimeInHours, TSurfF(i), Temperatures(PipesLevelElement,i), TSurfC(i), Tair(i), TOp(i),
     TSurfW(i)

     ENDIF

enddo

write(2,*)
```

```
! Main heat fluxes printing


write(2,*) 'Time     QsOnFloor         QsOnCeiling        QsOnWalls       QsToCircuit'

do i=0,NCalcTimeSteps

    IF (MOD(i*CalcTimeStep,600).eq.0) THEN

    TimeInHours=i*CalcTimeStep/3600.0

    write(2,6) TimeInHours, QsOnFloor(i), QsOnCeiling(i), QsOnWalls(i), QsToCircuit(i)

    ENDIF

enddo


write(6,*) 'Fine'

stop

end




! SUBROUTINES ____________________________________________________________________


! Subroutine "ReadSlabAndLoads": it reads the values of materials, characteristics of the circuit and boundary
conditions, according with an external file named "InitialData.txt" and enclosed in the present Standard



Subroutine ReadSlabAndLoads (hFloorToCeiling, hAirToFloor, hAirToCeiling, UpperResistance,
LowerResistance, WallsResistance, Rtot, hAirToWalls, hSlabToWalls, NLayersUp, NLayersDown, Layers,
UpperElement, PipesLevelElement, LowerElement, FloorArea, AreaWalls, TimeStep, WallsInertia, NSteps,
NTimes, TimeCycle, TotalTime, Boundary, FvSlabToExtWall, FvFloorToCeiling, OutputFile, CalcTimeStep)



Implicit none



! Definition of the Types involved by "ReadSlabAndLoads"



Type        Layer

            Character*1       Kind
```

```
          Integer        NElements

          Real           Thickness

          Real           Lambda

          Real           SpecHeat

          Real           Rho

          Real           Resistance

          Integer        InitialElement

          Integer        FinalElement

          Real           ElThickness

End Type  Layer


Type      HeatLoadsAndCircuit

          Integer        Time

          Integer        RunningMode

          Real           Twater

          Real           RadiantHeatFlux

          Real           ConvectiveHeatFlux

          Real           QAir

EndType HeatLoadsAndCircuit


! Definition of the variables involved by "ReadSlabAndLoads"


          Type           (Layer)::               Layers(1:20)

          Type           (HeatLoadsAndCircuit):: Boundary(0:320000)


          Real           hFloorToCeiling

          Real           FvFloorToCeiling

          Real           hAirToFloor

          Real           hAirToCeiling
```

```
Real            UpperResistance
Real            LowerResistance
Real            WallsResistance
Real            Rtot
Real            hAirToWalls
Real            hSlabToWalls
Real            FvSlabToExtWall
Integer         NLayersUp
Integer         NLayersDown
Integer         UpperElement
Integer         PipesLevelElement
Integer         LowerElement
Real            FloorArea
Real            AreaWalls
Integer         TimeStep
Real            WallsInertia
Integer         NSteps
Integer         NTimes
Integer         TimeCycle
Integer CalcTimeStep
Integer         TotalTime
Character*32    OutputFile
Real            Trash                 ! Support variable
Character*100 TrashC                  ! Support variable
Integer i                             ! Support counter
```

```
! Subroutine "ReadSlabAndLoads"_______________________________________________________________

! Opening the input file and inizialization of the variables

        Open(unit=1, file='ART_W_TS_CONT_KOS.txt', status='old')

        hFloorToCeiling = 0

        hAirToFloor = 0

        hAirToCeiling = 0

        UpperResistance = 0

        LowerResistance = 0

        FvFloorToCeiling = 0

        FvSlabToExtWall = 0

        Rtot = 0

        hAirToWalls = 0

        hSlabToWalls = 0

        NLayersUp = 0

        NLayersDown = 0

        do i = 1, 20

                Layers(i).Kind = 'N'

                Layers(i).NElements = 0

                Layers(i).Thickness = 0

                Layers(i).Lambda = 0

                Layers(i).SpecHeat = 0

                Layers(i).Rho = 0

                Layers(i).Resistance = 0

                Layers(i).InitialElement = 0

                Layers(i).FinalElement = 0

                Layers(i).ElThickness = 0
```

```
        enddo

        UpperElement = 0

        PipesLevelElement = 0

        LowerElement = 0

        FloorArea = 0

        AreaWalls = 0

        TimeStep = 0

        WallsInertia = 0

        NSteps = 0

        NTimes = 0

        TimeCycle = 0

        CalcTimeStep = 0

        TotalTime = 0

        do i = 0, 320000

                Boundary(i).Time = 0

                Boundary(i).RunningMode = 0

                Boundary(i).Twater = 0

                Boundary(i).RadiantHeatFlux = 0

                Boundary(i).ConvectiveHeatFlux = 0

                Boundary(i).QAir = 0

        enddo


! Reading the input data from the file "InitialData.txt"


        READ(1,*)

        READ(1,*)

        READ(1,*)

        Read(1,*) OutputFile

        READ(1,*)
```

```
READ(1,*) FvFloorToCeiling, FvSlabToExtWall, hAirToFloor, hAirToCeiling, hAirToWalls, Rtot, UpperResistance, LowerResistance, WallsResistance

READ(1,*)

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

hFloorToCeiling = FvFloorToCeiling*4*300**3*5.67/10**8*0.9

Read (1,*) TrashC, NLayersUp

Read (1,*)

Read (1,*)



do i = 1, NLayersUp

    Read (1,*) Layers(i).Kind, Layers(i).NElements, Layers(i).Thickness, Layers(i).Lambda, Layers(i).SpecHeat, Layers(i).Rho, Layers(i).Resistance

    if (Layers(i).Kind.eq.'R') then

        Layers(i).NElements = 0

        Layers(i).Thickness = 0

        Layers(i).Lambda = 0

        Layers(i).SpecHeat = 0

        Layers(i).Rho = 0

    endif

    if (i.eq.1) then

        Layers(i).InitialElement = 1

    else

        if (Layers(i).Kind.eq.'R') then

            Layers(i).InitialElement = Layers(i-1).FinalElement

        else

            Layers(i).InitialElement = Layers(i-1).FinalElement+1

        endif

    endif

    if (Layers(i).Kind.eq.'R') then

        Layers(i).FinalElement = Layers(i).InitialElement
```

```
          else

                    Layers(i).FinalElement = Layers(i).InitialElement + Layers(i).NElements-1

          endif

          if (Layers(i).Kind.eq.'R') then

                    Layers(i).ElThickness = 0

          else

                    Layers(i).ElThickness = Layers(i).Thickness/Layers(i).NElements

          endif

enddo


do i = 1, 6-NLayersUp

          Read (1,*)

enddo


Read (1,*) TrashC, NLayersDown

Read (1,*)

Read (1,*)


do i = NLayersUp+1, NLayersUp+NLayersDown

          Read (1,*) Layers(i).Kind, Layers(i).NElements, Layers(i).Thickness, Layers(i).Lambda,
          Layers(i).SpecHeat, Layers(i).Rho, Layers(i).Resistance

          if (Layers(i).Kind.eq.'R') then

                    Layers(i).NElements = 0

                    Layers(i).Thickness = 0

                    Layers(i).Lambda = 0

                    Layers(i).SpecHeat = 0

                    Layers(i).Rho = 0

          endif

          if (i.eq.NLayersUp+1) then

                    Layers(i).InitialElement = Layers(i-1).FinalElement
```

```
          else
                    if (Layers(i).Kind.eq.'R') then
                              Layers(i).InitialElement = Layers(i-1).FinalElement
                    else
                              Layers(i).InitialElement = Layers(i-1).FinalElement+1
                    endif
          endif
          if (Layers(i).Kind.eq.'R') then
                    Layers(i).FinalElement = Layers(i).InitialElement
          else
                    Layers(i).FinalElement = Layers(i).InitialElement + Layers(i).NElements - 1
          endif
          if (Layers(i).Kind.eq.'R') then
                    Layers(i).ElThickness = 0
          else
                    Layers(i).ElThickness = Layers(i).Thickness/Layers(i).NElements
          endif
enddo

UpperElement = 1
PipesLevelElement = Layers(NLayersUp).FinalElement
LowerElement = Layers(NLayersUp+NLayersDown).FinalElement

do i = 1, 5-NLayersDown
          Read (1,*)
enddo

Read(1,*) TrashC, FloorArea, TrashC, TrashC, AreaWalls
Read(1,*)
```

```
    Read(1,*) TrashC, TrashC, TimeStep, TrashC, TrashC, WallsInertia
    Read(1,*)
    Read(1,*) TrashC, NSteps
    Read(1,*) TrashC, CalcTimeStep
    Read(1,*) TrashC, NTimes
    Read(1,*)
    Read(1,*)

    do i=0,NSteps
        Boundary(i).Time=TimeStep*i
        Read(1,*) Trash, Trash, Trash, Trash, Trash, Trash, Boundary(i).ConvectiveHeatFlux, Boundary(i).RadiantHeatFlux, Boundary(i).Qair, Boundary(i).RunningMode, Boundary(i).Twater
    enddo


! Creation of the total list of boundary conditions, taking into account the number of times the boundary load conditions must be repeated

    TimeCycle = NSteps*TimeStep
    TotalTime = TimeCycle * NTimes
    do i=NSteps+1,NTimes*NSteps
        Boundary(i).Time = i*TimeStep
        Boundary(i).RunningMode = Boundary(Mod(i,NSteps)).RunningMode
        Boundary(i).Twater = Boundary(Mod(i,NSteps)).Twater
        Boundary(i).RadiantHeatFlux = Boundary(Mod(i,NSteps)).RadiantHeatFlux
        Boundary(i).ConvectiveHeatFlux = Boundary(Mod(i,NSteps)).ConvectiveHeatFlux
        Boundary(i).QAir = Boundary(Mod(i,NSteps)).QAir
    enddo
return
EndSubroutine
```

```
! Subroutine "CreateInterfaces": it uses the input data concerning the slab in order to define the characteristics
of each interface dividing the slab


Subroutine CreateInterfaces (UpperResistance, LowerResistance, NLayersUp, NLayersDown, Layers,
UpperElement, PipesLevelElement, LowerElement, Element)


Implicit none


! Definition of the Types involved by "CreateInterfaces"


Type        Layer

            Character*1     Kind

            Integer         NElements

            Real            Thickness

            Real            Lambda

            Real            SpecHeat

            Real            Rho

            Real            Resistance

            Integer         InitialElement

            Integer         FinalElement

            Real            ElThickness

End Type    Layer


Type        El

            Real            Capacity

            Real            ResistanceUp

            Real            ResistanceDown

            Integer         ExtH

End Type    El
```

```
! Definition of the variables involved by "CreateInterfaces"


        Type            (Layer)::           Layers(1:20)

        Type            (El)::              Element(1:50)


        Real            UpperResistance

        Real            LowerResistance

        Integer         NLayersUp

        Integer         NLayersDown

        Integer UpperElement

        Integer PipesLevelElement

        Integer LowerElement

        Integer         NElementsUp

        Integer         NElementsDown

        Integer i                           ! Support counter

        Integer j                           ! Support counter

        Integer k                           ! Support counter



! Subroutine "CreateInterfaces"___________________________________________________________


        NElementsUp = Layers(NLayersUp).FinalElement

        NElementsDown = Layers(NLayersUp+NLayersDown).FinalElement-
                                            Layers(NLayersUp).FinalElement


! Inizialization of the variables


    do  i = 1, 50

        Element(i).Capacity = 0

        Element(i).ResistanceUp = 0
```

```
            Element(i).ResistanceDown = 0

            Element(i).ExtH = 0

        enddo


! Definition of the characteristics of the first element (starting from the floor)


        Element(1).Capacity = Layers(1).ElThickness*Layers(1).SpecHeat*Layers(1).Rho

        Element(1).ResistanceUp = UpperResistance + (Layers(1).ElThickness/2)/Layers(1).Lambda

        if ((1.eq.Layers(1).FinalElement).and.(Layers(2).Kind.eq.'R')) then

            Element(1).ResistanceDown =
            Layers(2).Resistance/2+(Layers(1).ElThickness/2)/Layers(1).Lambda

        else

            Element(1).ResistanceDown = (Layers(1).ElThickness/2)/Layers(1).Lambda

        endif

        Element(1).ExtH = 0


! Definition of the characteristics of the middle interfaces (starting from the floor)


        do  i = 2, NElementsUp-1

            do j=1, NLayersUp

            if (((i.ge.Layers(j).InitialElement).and.(i.le.Layers(j).FinalElement)).and.(Layers(j).Kind.ne.'R'))
            then

                Element(i).Capacity = Layers(j).ElThickness*Layers(j).SpecHeat*Layers(j).Rho

                if ((i.eq.Layers(j).InitialElement).and.(Layers(j-1).Kind.eq.'R')) then

                    Element(i).ResistanceUp = Layers(j-1).Resistance/2+(Layers(j).ElThickness/2) /
                    Layers(j).Lambda

                else

                Element(i).ResistanceUp = (Layers(j).ElThickness/2)/Layers(j).Lambda

                endif

                if ((i.eq.Layers(j).FinalElement).and.(Layers(j+1).Kind.eq.'R')) then
```

```
                    Element(i).ResistanceDown = Layers(j+1).Resistance/2+(Layers(j).ElThickness/2) / Layers(j).Lambda

                else

                Element(i).ResistanceDown = (Layers(j).ElThickness/2)/Layers(j).Lambda

                endif

                Element(i).ExtH = 0

                goto 10

            endif

10          enddo

        enddo



        Element(NElementsUp).Capacity = Layers(NLayersUp).ElThickness*Layers(NLayersUp).SpecHeat*Layers(NLayersUp).Rho + Layers(NLayersUp+1).ElThickness*Layers(NLayersUp+1).SpecHeat*Layers(NLayersUp+1).Rho

        if ((NElementsUp.eq.Layers(NLayersUp).InitialElement).and.(Layers(NLayersUp-1).Kind.eq.'R')) then

            Element(NElementsUp).ResistanceUp = Layers(NLayersUp-1).Resistance/2+(Layers(NLayersUp).ElThickness)/Layers(NLayersUp).Lambda

        else

            Element(NElementsUp).ResistanceUp = (Layers(NLayersUp).ElThickness)/Layers(NLayersUp).Lambda

        endif

        if ((NElementsUp.eq.Layers(NLayersUp+1).FinalElement).and.(Layers(NLayersUp+2).Kind.eq.'R')) then

            Element(NElementsUp).ResistanceDown = Layers(NLayersUp+2).Resistance/2+(Layers(NLayersUp+1).ElThickness)/Layers(NLayersUp+1).Lambda

        else

            Element(NElementsUp).ResistanceDown = (Layers(NLayersUp+1).ElThickness)/Layers(NLayersUp+1).Lambda

        endif

        Element(NElementsUp).ExtH = 1



        do  i = NElementsUp+1, NElementsUp+NElementsDown

            do j=NLayersUp+1, NLayersUp+NLayersDown
```

```
            if (((i.ge.Layers(j).InitialElement).and.(i.le.Layers(j).FinalElement)).and.(Layers(j).Kind.ne.'R'))
            then

                  Element(i).Capacity = Layers(j).ElThickness*Layers(j).SpecHeat*Layers(j).Rho

                  if ((i.eq.Layers(j).InitialElement).and.(Layers(j-1).Kind.eq.'R')) then

                        Element(i).ResistanceUp = Layers(j-1).Resistance/2+(Layers(j).ElThickness/2) /
                        Layers(j).Lambda

                  else

                        Element(i).ResistanceUp = (Layers(j).ElThickness/2)/Layers(j).Lambda

                  endif

                  if ((i.eq.Layers(j).FinalElement).and.(Layers(j+1).Kind.eq.'R')) then

                        Element(i).ResistanceDown = Layers(j+1).Resistance/2+(Layers(j).ElThickness/2)
                        / Layers(j).Lambda

                  else

                        Element(i).ResistanceDown = (Layers(j).ElThickness/2)/Layers(j).Lambda

                  endif

                  Element(i).ExtH = 0

                  goto 11

            endif

11          enddo

      enddo


! Definition of the characteristics of the first element (starting from the ceiling)


      Element(LowerElement).Capacity =
      Layers(NLayersUp+NLayersDown).ElThickness*Layers(NLayersUp+NLayersDown).SpecHeat*Layers(
      NLayersUp+NLayersDown).Rho

      if ((LowerElement.eq.Layers(NLayersUp+NLayersDown).InitialElement) .and.
      (Layers(NLayersUp+NLayersDown-1).Kind.eq.'R')) then

            Element(LowerElement).ResistanceUp = Layers(NLayersUp+NLayersDown-
            1).Resistance/2+(Layers(NLayersUp+NLayersDown).ElThickness/2)/Layers(NLayersUp+NLayer
            sDown).Lambda

      else

            Element(LowerElement).ResistanceUp =
            (Layers(NLayersUp+NLayersDown).ElThickness/2)/Layers(NLayersUp+NLayersDown).Lambda
```

```
     endif

     Element(LowerElement).ResistanceDown = LowerResistance +
     (Layers(NLayersUp+NLayersDown).ElThickness/2)/Layers(NLayersUp+NLayersDown).Lambda

     Element(LowerElement).ExtH = 0



return

EndSubroutine




! Subroutine "CreateTempAndFluxesTables": it calculates the values of temperatures and heat fluxes of air,
slab and walls



Subroutine CreateTempAndFluxesTables (hFloorToCeiling, hAirToFloor, hAirToCeiling, UpperResistance,
LowerResistance, WallsResistance, Rtot, hAirToWalls, hSlabToWalls, NLayersUp, NLayersDown, Element,
UpperElement, PipesLevelElement, LowerElement, FloorArea, AreaWalls, TimeStep, WallsInertia, NSteps,
NTimes, TimeCycle, TotalTime, Boundary, Temperatures, Tair, TWalls, QsOnFloor, QsOnCeiling, QsOnWalls,
QsToCircuit, CalcTimeStep, NCalcTimeSteps, TOp, TsurfW, TsurfC, TSurfF)



Implicit none



! Definition of the Types involved by "CreateTempAndFluxesTables"



Type        El

            Real            Capacity

            Real            ResistanceUp

            Real            ResistanceDown

            Integer         ExtH

End Type    El



Type        HeatLoadsAndCircuit

            Integer         Time

            Integer         RunningMode
```

```
        Real            Twater
        Real            RadiantHeatFlux
        Real            ConvectiveHeatFlux
        Real            QAir
EndType HeatLoadsAndCircuit


! Definition of the variables involved by "CreateTempAndFluxesTables"


        Type(El)::      Element(1:50)
        Type (HeatLoadsAndCircuit)::        Boundary(0:320000)


        Real            hFloorToCeiling
        Real            hAirToFloor
        Real            hAirToCeiling
        Real            UpperResistance
        Real            LowerResistance
        Real            WallsResistance
        Real            Rtot
        Real            hAirToWalls
        Real            hSlabToWalls
        Integer         NLayersUp
        Integer         NLayersDown
        Integer UpperElement
        Integer PipesLevelElement
        Integer LowerElement
        Real            FloorArea
        Real            AreaWalls
        Integer         TimeStep
        Real            WallsInertia
```

```
Integer           NSteps
Integer           NTimes
Integer           TimeCycle
Integer TotalTime
Integer           CalcTimeStep
Integer NCalcTimeSteps
Real              Temperatures(1:50,0:640000)
Real              Tair(0:640000)
Real              TWalls(0:640000)
Real              qsOnFloor(0:640000)
Real              qsOnCeiling(0:640000)
Real              qsOnWalls(0:640000)
Real              qsToCircuit(0:640000)
Real              TOp(0:640000)
Integer           RunningMode            ! Support variable
Real              Twater                 ! Support variable
Real              RadiantHeatFlux        ! Support variable
Real              ConvectiveHeatFlux     ! Support variable
Real              QAir                   ! Support variable
Real              qOnFloor               ! Support variable
Real              qOnCeiling             ! Support variable
Real              RCAC                   ! Convective thermal resistance Air-Ceiling
Real              RRWC                   ! Radiant thermal resistance Walls-Ceiling
Real              RRFC                   ! Radiant thermal resistance Floor-Ceiling
Real              RCAW                   ! Convective thermal resistance Air-Walls
Real              RRWF                   ! Radiant thermal resistance Walls-Floor
Real              RCAF                   ! Convective thermal resistance Air-Floor
Real              QRadW                  ! Radiant heat loads acting onto the walls
Real              QRadF                  ! Radiant heat loads acting onto the floor
```

```
        Real        QRadC             ! Radiant heat loads acting onto the ceiling
        Real        QRadWF            ! Radiant heat flux acting from the walls onto the floor
        Real        QRadWC            ! Radiant heat flux acting from the walls onto the ceiling
        Real        QRadFC            ! Radiant heat flux acting from the floor onto the ceiling
        Real        QConvW            ! Convective heat loads acting onto the walls
        Real        QConvF            ! Convective heat loads acting onto the floor
        Real        QConvC            ! Convective heat loads acting onto the ceiling
        Real        TSurfW(0:640000)
        Real        TSurfC(0:640000)
        Real        TSurfF(0:640000)

        Integer i                     ! Support counter
        Integer j                     ! Support counter
        Integer k                     ! Support counter


! Subroutine "CreateTempAndFluxesTables"____________________________________________

! Calculation of the number of times the calculation must be performed

    NCalcTimeSteps=TotalTime/CalcTimeStep

! Inizialization of the variables

    do i = 0,640000
        do j = 1,50
            Tair(i) = 0
            TWalls(i)= 0
            Temperatures(j,i)= 0
```

```
          enddo


          TOp(i) = 0

          TWalls(i) = 0

          qsOnFloor(i) = 0

          qsOnCeiling(i) = 0

          qsOnWalls(i) = 0

          qsToCircuit(i) = 0

          TSurfW(i) = 0

          TSurfF(i) = 0

          TSurfC(i) = 0

enddo


do j=1,50

          Temperatures(j,0)=22.

enddo


TOp(0) = 22.

Tair(0) = 22.

TWalls(0) = 22.

TSurfW(0) = 22.

TSurfF(0) = 22.

TSurfC(0) = 22.


do i=1, NCalcTimeSteps

          do j=1, NTimes*NSteps

                    if ((i*CalcTimeStep.gt.Boundary(j-1).Time).and.(i*CalcTimeStep.le.Boundary(j).Time))
                    then

                              RunningMode=Boundary(j).RunningMode

                              Twater=Boundary(j).Twater
```

```
                        RadiantHeatFlux=Boundary(j).RadiantHeatFlux

                        ConvectiveHeatFlux=Boundary(j).ConvectiveHeatFlux

                        QAir=Boundary(j).QAir

                        goto 12

                    endif

12          enddo


! Calculation of the involved resistances


            RCAC = (1/hAirToCeiling + Element(LowerElement).ResistanceDown)

            RRWC = (1/hSlabToWalls + WallsResistance*FloorArea/AreaWalls +
            Element(LowerElement).ResistanceDown )

            RRFC = (1/hFloorToCeiling + Element(1).ResistanceUp +
            Element(LowerElement).ResistanceDown)

            RCAW = (1/hAirToWalls + WallsResistance)

            RRWF = (1/hSlabToWalls + Element(1).ResistanceUp + WallsResistance*FloorArea/AreaWalls)

            RCAF = (1/hAirToFloor + Element(1).ResistanceUp)


! Calculation of the air temperature


            Tair(i) = (ConvectiveHeatFlux + QAir + AreaWalls/RCAW * TWalls(i-1) + FloorArea/RCAF *
            Temperatures(1,i-1) + FloorArea/RCAC * Temperatures(LowerElement,i-1)) / (AreaWalls/RCAW
            + FloorArea/RCAF + FloorArea/RCAC)


! Calculation of the heat fluxes acting on the internal surfaces


            QRadW = RadiantHeatFlux * AreaWalls/(2*FloorArea + AreaWalls)

            QRadF = RadiantHeatFlux * FloorArea/(2*FloorArea + AreaWalls)

            QRadC = RadiantHeatFlux * FloorArea/(2*FloorArea + AreaWalls)


            QRadWF = (TWalls(i-1) - Temperatures(1,i-1)) / RRWF * FloorArea
```

```
          QRadWC = (TWalls(i-1) - Temperatures(LowerElement,i-1)) / RRWC * FloorArea

          QRadFC = (Temperatures(1,i-1) - Temperatures(LowerElement,i-1)) / RRFC * FloorArea


          QConvW = (Tair(i)-TWalls(i-1))/RCAW * AreaWalls

          QConvF = (Tair(i)-Temperatures(1,i-1))/RCAF * FloorArea

          QConvC = (Tair(i)-Temperatures(LowerElement,i-1))/RCAC * FloorArea


          qOnFloor = (QRadF + QRadWF - QRadFC + QConvF)/FloorArea

          qOnCeiling = (QRadC + QRadWC + QRadFC + QConvC)/FloorArea


! Calculation of the temperatures of the walls and the slab interfaces


          TWalls(i) = (QRadW - QRadWF - QRadWC + QConvW)*CalcTimeStep/ (WallsInertia *
          AreaWalls) +  TWalls(i-1)


          Temperatures(1,i)=(qOnFloor+(Temperatures(2,i-1)-Temperatures(1,i-1)) /
          (Element(1).ResistanceDown+Element(2).ResistanceUp))*CalcTimeStep/Element(1).Capacity +
          Temperatures(1,i-1)


          do k=2,LowerElement-1

                Temperatures(k,i)= ((Temperatures(k-1,i-1)-Temperatures(k,i-1)) /
                (Element(k).ResistanceUp+Element(k-1).ResistanceDown)+(Temperatures(k+1,i-1) -
                Temperatures(k,i-1))/(Element(k).ResistanceDown+Element(k+1).ResistanceUp) +
                (Twater-Temperatures(k,i-1))*RunningMode/Rtot*Element(k).ExtH)*CalcTimeStep /
                Element(k).Capacity+Temperatures(k,i-1)

          enddo


          Temperatures(LowerElement,i)=(qOnCeiling+(Temperatures(LowerElement-1,i-1) -
          Temperatures(LowerElement,i-1))/(Element(LowerElement).ResistanceUp +
          Element(LowerElement-1).ResistanceDown))*CalcTimeStep/Element(LowerElement).Capacity +
          Temperatures(LowerElement,i-1)


          TSurfF(i)=QOnFloor*Element(1).ResistanceUp+Temperatures(1,i)

          TSurfC(i)=QOnCeiling*Element(LowerElement).ResistanceDown+Temperatures(LowerElement,i)
```

```
        TSurfW(i) = TWalls(i) + (QRadW - QRadWF - QRadWC + QConvW)/AreaWalls *
        WallsResistance


! Last outputs definition


        qsOnFloor(i)=qOnFloor

        qsOnCeiling(i)=qOnCeiling

        qsOnWalls(i) = (QRadW - QRadWF - QRadWC + QConvW) / FloorArea

        QsToCircuit(i)=(Twater-Temperatures(PipesLevelElement,i))*RunningMode/Rtot

        TOp(i)=((TSurfF(i)*FloorArea+TSurfC(i)*FloorArea+TSurfW(i)*AreaWalls) /
        (FloorArea*2+AreaWalls)+Tair(i))/2


    enddo


return

EndSubroutine
```

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