NANDRAD 1.4 building simulation model

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Contents

Symbol	Base unit	Description
t	s	Time
T	K	Temperature
T_{op}	K	Operative temperature
T_{rad}	K	Radiant temperature
ϱ	kg/m^3	Mass density per unit volume
c	J/kgK	Specific heat capacity
C_M	J/K	Heat capacity of storage mass
λ	W/mK	Thermal conductivity
α	W/m^2K	Heat transfer coefficient
a	[0..1]	Adsorbtion rate of solar radiation
τ	[0..1]	Transmission rate of solar radiation
r	[0..1]	Reflection rate of solar radiation
ε	[0..1]	Emission rate of long wave radiation
σ	J/K	Boltzmann constant.
Φ	[0..1]	View factor between a point and a surface/ different surfaces
A	m^2	Area
A_R	m^2	Zone floor area
V	m^3	Volume
d	m	Thickness of a construction layer
γ_{conv}	[0..1]	Rate of convective loads
γ_{rad}	[0..1]	Rate of radiant loads
$\gamma_{visible}$	[0..1]	Rate of visible loads
f_F	[0..1]	Frame factor of a window
z	[0..1]	Shading factor of an external surface or a window
U	W/m^2K	Heat transmission coefficient, U-value
n	$1/s$	Air change rate
$\dot{m}$	kg/s	Mass flux
N_P		Maximum number of persons inside a room
$f_P(t)$	[0..1]	Person occupancy fraction
$f_E(t)$	[0..1]	Electric equipment utilization fraction
$f_L(t)$	[0..1]	Lighting utilization fraction
$\dot{Q}$	$W = J/s$	Heat flux
q	W/m^2	Heat flux density
$q_{rad,i}$	W/m^2	Global solar radiation at an inclined surface
q_{ex}	W/m^2	Heat flux density due to long wave radiation exchange
$\dot{u}$	W/m^3	Heat source inside a volume
e	W/m^2	Long wave radiation intrinsic emission of an inside surface
j	W/m^2	Long wave radiosity of an inside surface
h	W/m^2	Long wave irradiance of an inside surface
$\dot{Q}_{act}$	W	Load from person activity
$\dot{Q}_{loss}$	W	Thermal losses from person occupancy
$\dot{u}_{elec}$	W/m^2	Maximum thermal load from equipment per zone floor area
$\dot{u}_{lights}$	W/m^2	Maximum thermal load from lighting per zone floor area

Table 1: List of symbols

Symbol	Description
ψ	Abstract physical quantity
ψ_{air}	Physical quantity of dry air
ψ_R	Physical quantity of a zone
ψ_e	Ambient physical quantity
ψ_W	Physical quantity of a wall surface

ψ_F	Physical quantity of a window inside surface
ψ_H	Physical quantity due to zone heating
ψ_C	Physical quantity due to zone cooling
ψ_{AB}	Physical quantity inside active elements of constructions
ψ_{conv}	Convective transport flux/ flux density
ψ_{rad}	Radiant transport flux/ flux density
ψ_{LWRad}	Long wave radiation transport flux/ flux density
ψ_{SWRad}	Short wave radiation transport flux/ flux density
ψ_{trans}	Transmission transport flux/flux density
ψ_N	Quantity due to natural ventilation
ψ_I	Quantity due to infiltration
ψ_P	Quantity due to person occupancy
ψ_E	Quantity due to equipment
ψ_L	Quantity due to lighting

Table 2: List of indices

1 Introduction

NANDRAD is a platform for the dynamic energy simulation of complex buildings. It is developed as an multizone extension of the singlezone model THERAKLES [2]. The dynamic energy demand and storage of the building with regard to its occupants and realistic usage scenarios is central to the view of both programs. As a result, the integrated physical building component models are quite detailed. In particular, massive constructions in the European area are well represented by spatially discretized constructions.

The scope of NANDRAD development is on the multizone simulation of complex buildings. Resulting in a large model size, current approach focuses on large-scale simulation and modelling techniques. NANDRAD data format as well as numerical NANDRAD solver were specifically optimized for energy simulation of large buildings. Further, NANDRAD supports advanced coupling techniques with external technical building equipment model libraries and interaction with external GUI developers, for example via the Functional Mockup Interface. The program is a command line solver without graphical user interface. There exist export/conversion tools from other building energy simulation programs and their data formats i.e. IDF (EnergyPlus/DesignBuilder). The commercial software BIMHVACTool directly supports NANDRAD. Details of the of the data format used by NANDRAD are documented at the NANDRAD webpage [1].

2 NANDRAD multi-zone building model

2.1 Fundamentals

NANDRAD is a multi-zone building energy simulation model. As a non-geometric model, it idealizes the actual geometry of the building as a network of interconnected zones. Zones are indirectly connected through walls, floors and ceilings, which are represented by individual building component models. The building can be considered as a graph of rooms and adjacent building components (e.g. wall constructions) as illustrated in Figure 1.

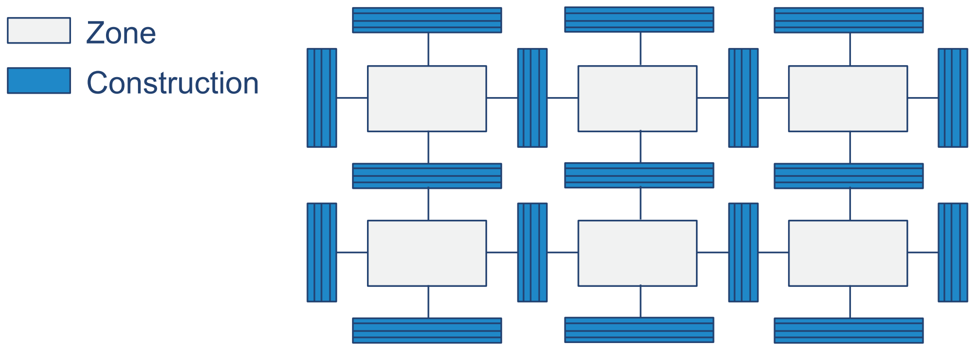

Figure 1: Building represented by a model network

When modeling buildings, rooms with same/similar properties and usage may be jointly represented as one zone. Interior separation walls, inside the merged rooms, shall be considered as additional thermal storage masses in this zone, similarly to furniture and other thermal storage masses. Zones are idealized as well-mixed air spaces with a mean zone air temperature and all thermal storage masses have the same temperature. The dynamic changes of zone temperatures is described in a differential equation (see balance equation 3.1).

2.2 Building component models

Building walls/floors/ceilings/roofs are modeled as one-dimensional multilayered constructions with different material properties per layer, such as thermal conductivity and heat storage capacity. The solution of a transient balance equation with detailed view on thermal storage is one of the capabilities of NANDRAD model. As there exists no simple analytical approach for multilayered building constructions, we spatially discretize the transient transport processes through each wall in one space dimension. As a consequence, we solve a set of balance equations and obtain a discretized temperature field. A special feature of NANDRAD is the support of heat sources inside wall constructions. In detail, each construction layer can be assigned with a source or sink and may therefore represent an active building component.

The walls exchange heat with the neighboring rooms and visible walls at the surfaces. We consider different gains, e.g. heat exchange between inside wall and zone air, absorption of short wave radiation, long wave radiation exchange, radiant heating gains or long wave radiation gains by building usage (person occupancy, electric eqipment and lighting load). Geometrical information is provided for selected transport mechanisms. For example, we use view factors to encapsulate geometrical wall position needed for long wave radiation exchange between all inside walls and window surfaces.

Windows are included in the model without regard to thermal storage.

2.3 Building services and usage

Usage of the building such as person occupancy, heating, cooling or ventilation are considered as loads for room air and wall energy balances. For this purpose, the balance equations provide source terms that collect loads from heating/cooling or other plant components with impact on building energy balance. In general, convective loads impact room air balance, while radiant loads are distributed towards all wall surfaces.

2.4 Climatic model

Climate calculations are performed by an external library [3]. The climatic model interpolates temperature, direct and diffuse radiation at each simulation time point. Further, it calculates the portion of global solar radiation on each surface with a given inclination and orientation without regard to external shading.

3 Model equations

The description of the physical model begins with the transient balance equations for energy conservation in rooms/thermal zones and opaque constructions (walls, floors, ceiling, etc.). A discussion of the individual loads and heat flow quantities contained within the balance equations follows.

3.1 Balance equations

Zone energy balance

We interpret a room/space as a thermal zone node with volume V_R owning a mean air temperature T_R and internal energy Q_R. The room is filled with dry air. Further, furniture/internal masses significantly increase the thermal storage capability of the zone volume whereby the temperature of these additional masses is assumed to be always equal to the room air temperature. The relation between zone temperature and internal energy is given by:

$$Q_R = \left(c_{air}\rho_{air}V_R + C_M\right)T_R$$

C_M is the heat storage capacity of included furniture/additional storage masses. The dynamic change of the zonal temperature is governed by an energy balance equation:

$$\begin{aligned}\frac{\mathrm{d}Q_R}{\mathrm{d}t} = \dot{Q}_N + \dot{Q}_I + \sum_i^{n_F}\dot{Q}_{F,trans,i} + \sum_i^{n_W}\dot{Q}_{W,conv,i} + \sum_i^{n_C}\dot{Q}_{C,i} + \sum_i^{n_H}\dot{Q}_{H,conv,i} \\ +\gamma_{SW,conv}\sum_i^{n_F}\dot{Q}_{SWRad,i} + \dot{Q}_{P,conv} + \dot{Q}_{E,conv} + \dot{Q}_{L,conv}\end{aligned}$$

Internal energy changes with time due to natural ventilation heat loads $\dot{Q}_N$, infiltration loads $\dot{Q}_I$, heat conduction fluxes through the surrounding wall constructions $\dot{Q}_{W,conv,i}$, transmission fluxes through windows $\dot{Q}_{F,trans,i}$, internal cooling loads $\dot{Q}_{C,i}$, convective heating loads $\dot{Q}_{H,conv,i}$, convectively transfered gains of incoming short wave radiation $\gamma_{SWRad}\dot{Q}_{SWRad,i}$ and convective person, equipment and lighting loads $\dot{Q}_{P,conv}$, $\dot{Q}_{E,conv}$, $\dot{Q}_{L,conv}$. Solar radiation gains through windows both are adsorbed by internal walls and heat up room air directly. The coefficient $\gamma_{SW,conv}$ denotes the fraction of short wave radiation that is converted into heat gains for room air balance.

Construction energy balance

The wall constructions are considered as one dimensional multilayered compound structures of different materials over the wall thickness. Each material itself is treated as continuum allowing thermal storage and conduction heat transfer. These requirements are satisfied by the transient heat equation with u denoting the the internal energy density as solution quantity:

$$\frac{\partial u}{\partial t} = -\frac{\partial}{\partial x}q + \dot{u}_{AB}$$

The relation between temperature T and internal energy density u is given by:

$$u = c\rho T$$

where specific heat capacity c, dry bulk density ρ are parameters of the respective material layers. Transient changes of internal energy density are caused by conduction flux density q.

$$q = -\lambda\frac{\partial T}{\partial x}$$

Thermal conductivity λ varies for each wall material layer. Further, we allow heat sources inside each construction layer $\dot{u}_{AB}$ that represent thermal active building components.

3.2 Construction balance boundary conditions

Boundary condition model for inside surfaces

At the inside wall surface several heat transfer mechanisms are present: the convective heat transfer between wall surface and room air $q_{conv,W,i}$, heat gains due to short wave radiation heat flux densities $q_{SWRad,W,i}$ and long wave radiation heat flux densities $q_{LWRad,W,i}$. We define all fluxes positively towards the wall.

$$q_{W,i} = q_{conv,W,i} + q_{SWRad,W,i} + q_{LWRad,W,i}$$

The convective heat transfer between the wall surface and the room air is considered as a boundary layer phenomena caused by the temperature gradient between mean room air T_R and wall surface temperature $T_{W,i}$.

$$q_{conv,W,i} = \alpha_{W,i} \left(T_R - T_{W,i}\right)$$

A fraction of the short wave radiation gains through windows $q_{SWRad,W}$ are distributed uniformely towards the inside wall surfaces:

$$q_{SWRad,W,i} = q_{SWRad,W}$$

If no detailed long wave radiation exchange is activated (missing view factors), the heat transfer coefficient $\alpha_{W,i}$ both includes convective mechanisms and long wave radiation heat transfer to other surfaces. The latter transport mechanism leads to a compensation of temperature gradients between different wall surfaces and is approximately described by heat exchange between the walls and the mean room air temperature between. If no geometrical information about the surfaces is available (i.e. no view factors), we assume a uniform distribution of long wave radiation loads from internal sources towards all inner wall surfaces. The long wave radiation fluxes result from radiant heating $q_{H,W}$, radiant loads from persons, equipment and lighting $q_{P,W}$, $q_{E,W}$ and $q_{L,W}$. If geometric detailed long wave radiation exchange of inside surfaces is considered, additionally we add heat flux density from heat exchange between current surface and all other visible surfaces $q_{ex,W,i}$.

$$q_{LWRad,W,i} = q_{H,W} + q_{P,W} + q_{E,W} + q_{L,W} + q_{ex,W,i}$$

Boundary condition model for outside surfaces

At the outside surface we consider heat fluxes due to heat exchange $q_{conv,W,i}$ with ambient air temperature $T_e\left(t\right)$, and gains by direct and diffuse solar radiation $q_{SWRad,W,i}$.

$$q_{conv,W,i} = \alpha_{W,i} \left(T_e\left(t\right) - T_{W,i}\right)$$

Hereby, $a_{W,i}$ is the solar adsorbtion coefficient and $q_{rad,i}$ the gross short wave radiation flux in direction of the surface normal. Regarding the lack of information due to surrounding buildings, long wave radiation heat gains are not explicitely considered but included in the convective heat transfer. Note, that we interpret the coefficient $\alpha_{W,i}$ as mixed convective and radiant transfer coefficient and expect a properly increased parameter value.

Boundary condition model for adiabatic surfaces

Adiabatic wall surfaces do not provide heat fluxes.

$$\begin{aligned} q_{conv,W,i} &= 0 \\ q_{SWRad,W,i} &= 0 \\ q_{LWRad,W,i} &= 0 \end{aligned}$$

3.3 Construction energy sources/sinks

Additional energy sources/sinks for wall balances can be applied to each construction layer of a wall. Such a source (heat gain) $\dot{Q}_{AB}$ is uniformely distributed across the corresponding layer with longitudal area A_W and thickness d and correspond to the volumetric heat source $\dot{u}_{AB}$ (see Figure 2).

$$\dot{u}_{AB} = \frac{\dot{Q}_{AB}}{A_W d}$$

This feature can be used to include thermal active construction elements in an idealized way. As it is illustrated in Figure 2 below, the modeller adds an active material layer to the construction and uniformly distributes all heat gains over the construction longitudinal area.

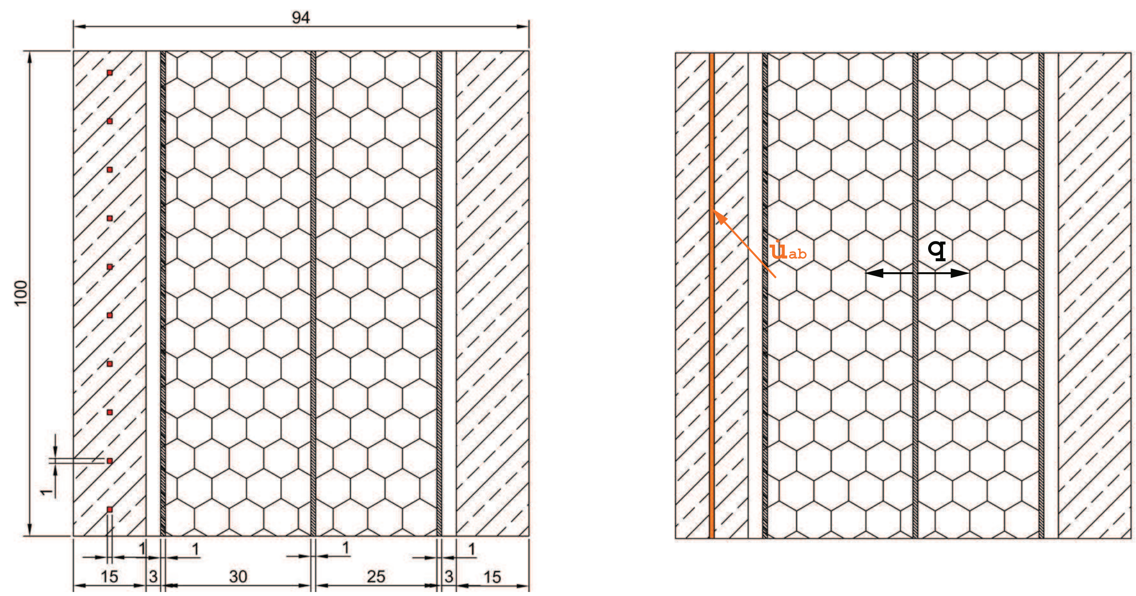

Figure 2: Wall with thermal active components (left, red dots indicating heated pipes) and its representation as a one dimensional heat source (right, orange layer).

3.4 Windows

We use a steady-state monolayer window model and calculate the transmitted solar radiation heat gains $\dot{Q}_{SWRad,F,i}$ as well as heat loads by heat transmission through the window $\dot{Q}_{Trans,F,i}$.

$$\begin{aligned}\dot{Q}_{SWRad,i} &= z_{F,i}\,\tau_{F,i}\,f_{F,i}\,q_{rad,i}A_{F,i}\\ \dot{Q}_{F,trans,i} &= U_{F,i}\left(T_e\left(t\right)-T_R\right)A_{F,i}\end{aligned}$$

Effect of shading is considered due to the constant shading coefficient $z_{F,i} \in [0,1]$ that describes the fraction of heat that is still transmitted through the shading. $\tau_{F,i} \in [0,1]$ is the angle-dependent solar heat gain coefficient. $f_{F,i} \in [0,1]$ denotes the fraction of the window glass.

The window surface temperature $T_{F,i}$ is calculated by the thermal resistance of the surface layer, with $\alpha_{F,i}$ denoting the heat transfer coefficient:

$$T_{F,i} = T_R + \frac{\dot{Q}_{F,trans,i}}{\alpha_{F,i}A_{F,i}}$$

3.5 Ambient environment

The following climate data components are used by NANDRAD:

- the ambient temperature $T_e(t)$
- the direct solar radiation in the sun's normal direction $q_{rad,dir}(t)$
- the diffuse solar radiation onto a horizontal surface $q_{rad,dif}(t)$

The solar radiation fluxes onto a surface i (window or wall outside surface) with given orientation and inclination are calculated by the Climate Calculation Module (see details in documentation [3]). The global solar radiation flux is then:

$$q_{rad,i} = q_{rad,dir,i} + q_{rad,dif,i}$$

With respect to external shading objects, the user can define time dependent external shading factors $z_{e,i}(t)$ for the period of one year, that only reduces the direct solar radiation.

$$q_{rad,i} = z_{e,i}(t)\, q_{rad,dir,i} + q_{rad,dif,i}$$

3.6 Zone internal loads

Occupancy

The occupancy of a room describes different usage scenarios with the help of schedules. We consider loads from the presence of persons, the usage of electric equipment and lighting. For this purpose we balance heat gains from person activity $\dot{Q}_{act}$ and heat reduction due to persons absorbing energy $\dot{Q}_{loss}$. The person-specific net heat gain is multiplied with the numimal/maximum person count N_P and a scheduled occupancy fraction $f_P(t)$:

$$\dot{Q}_P = N_P f_P(t) \left(\dot{Q}_{act} - \dot{Q}_{loss}\right)$$

Heat gains from electric equipment and lighting are described by maximim electric power per floor area $\dot{u}_{elec}$ (electric) and $\dot{u}_{light}$ (lighting), multiplied with a scheduled fraction utilization, $f_E(t)$ and $f_L(t)$, respectively:

$$\dot{Q}_E = f_E(t)\, \dot{u}_{elec} A_R$$
$$\dot{Q}_L = f_L(t)\, \dot{u}_{light} A_R$$

Each load is both transfered convectively to the room air and as long wave radiation towards the wall surfaces. We define ratios for the long wave radiation part of each load $\gamma_{P,rad}$, $\gamma_{E,rad}$ and $\gamma_{L,rad}$. Visible light relates to a ratio $\gamma_{L,visib}$ of lighting load.

$$\dot{Q}_{P,conv} = (1 - \gamma_{P,rad})\, \dot{Q}_P$$
$$\dot{Q}_{E,conv} = (1 - \gamma_{E,rad})\, \dot{Q}_E$$
$$\dot{Q}_{L,conv} = (1 - \gamma_{L,rad} - \gamma_{L,visib})\, \dot{Q}_L$$

Convective loads $\dot{Q}_{P,conv}$, $\dot{Q}_{E,conv}$ and $\dot{Q}_{L,conv}$ are obtained by excluding the energy that is emitted by long wave radiation $\dot{Q}_{P,rad}$, $\dot{Q}_{E,rad}$ and $\dot{Q}_{L,rad}$ as well as the visible lighting energy. While convective loads have an effect on room air balance, radiant loads are distributed towards the wall surfaces. Visible light is assumed to be immeditially transformed into radiant heat.

$$\dot{Q}_{P,rad} = \gamma_{P,rad} \dot{Q}_P$$
$$\dot{Q}_{E,rad} = \gamma_{E,rad} \dot{Q}_E$$
$$\dot{Q}_{L,rad} = (\gamma_{L,rad} + \gamma_{L,visib})\, \dot{Q}_L$$

Ideal heating and cooling

The room may be heated by an ideal heating with respect to the control temperature $T_{control}$ (air temperature or operative temperature). We use a P-control model with linear slope k_P and setpoint temperature $T_{setpoint}\left(t\right)$. Setpoint temperature is related to the usage scenario of the zone and defined by a schedule. For the purpose of robustness, we bound the heating loads $\dot{Q}_H$ by 0 and an upper limit given by a maximum heating power $\dot{Q}_{H,max}$.

$$\begin{aligned}\dot{Q}_{H,nominal} &= \max\left(0, k_P\left(T_{setpoint}\left(t\right) - T_{control}\right)\right)\\ \dot{Q}_H &= \min\left(\dot{Q}_{H,max}, \dot{Q}_{H,nominal}\right)\end{aligned}$$

In order to reach an optimal control result, we vary the heat transfer type according to the choice of control temperature. If zone air temperature is chosen as control quantity, we assume convective heating. If operative temperature is controled, we split heating power in an equal convective and radiant load.

$$\begin{aligned}\dot{Q}_{H,conv} &= \begin{cases}\dot{Q}_H & \text{if } T_{control} = T_R\\ 0.5\cdot\dot{Q}_H & \text{if } T_{control} = T_{op}\end{cases}\\ \dot{Q}_{H,rad} &= \dot{Q}_H - \dot{Q}_{H,conv}\end{aligned}$$

Cooling control is only allowed with respect to zone air temperature. Consequently, cooling only convective cooling is taken into account.

$$\begin{aligned}\dot{Q}_{C,nominal} &= \min\left(0, k_P\left(T_{setpoint}\left(t\right) - T_{control}\right)\right)\\ \dot{Q}_C &= \max\left(\dot{Q}_{C,min}, \dot{Q}_{C,nominal}\right)\end{aligned}$$

Heating point source

The point source model is simplest heating model. The heating load $\dot{Q}_{H,load}\left(t\right)$ is a scheduled input quantity being interpreted as convective or radiant load, whereby the constant parameter γ_H determines the fraction of radiant heating.

$$\begin{aligned}\dot{Q}_{H,rad} &= \gamma_H\dot{Q}_{H,load}\left(t\right)\\ \dot{Q}_{H,conv} &= \left(1-\gamma_H\right)\dot{Q}_{H,load}\end{aligned}$$

View factors for each inside surface to a point source $\Phi_{H,j}$ may be defined. In this case uniform distribution of long wave radiation gains towards all surfaces is substituted by individual calculation.

$$q_{H,W,j} = \Phi_{H,j}\frac{\gamma_H\dot{Q}_{H,rad}}{A_{W,j}}$$

Note, that windows do not absorb short wave or long wave radiation. For this reason, only long wave view factors are allowed that target solid room inside surfaces.

Natural ventilation

We take into consideration air conditioning due to natural ventilation and air exchange by infiltration. The corresponding air change rate for natural ventilation $n_L\left(t\right)$ correlates to user behaviour and needs to be provided by the schedules. The same way of parametrization is used for the infiltration air change rates $n_I\left(t\right)$. The supply air mass flux corresponds both to air change rate and zone volume V_R. We assume an ideal homogenious zone air with mass density ρ_{air} and heat capacity c_{air}.

$$\begin{aligned}\dot{m}_N &= \rho_{air}\, n_N\left(t\right)\, V_R\\ \dot{m}_I &= \rho_{air}\, n_I\left(t\right)\, V_R\end{aligned}$$

Our assumtions allow the calculation of enthalpy fluxes for the incoming and outgoing air with unique temperatures $T_e(t)$ and T_R.

$$\dot{Q}_N = \dot{m}_N \, c_{air} \left(T_e(t) - T_R\right)$$
$$\dot{Q}_I = \dot{m}_I \, c_{air} \left(T_e(t) - T_R\right)$$

3.7 Construction internal heat sources

Thermal active construction layer

An thermal active element is defined as a heat source inside a construction layer. The heating power is limited by a maximum value $\dot{Q}_{H,max}$ that correlates with real performance per default. We describe the operation of the heating element as an ideal P-control for control temperature $T_{control}$, setpoint temperature $T_{setpoint}(t)$ and slope k_P.

$$\dot{Q}_{H,nominal} = \max\left(0, k_P \left(T_{setpoint}(t) - T_{control}\right)\right)$$
$$\dot{Q}_{AB} = \min\left(\dot{Q}_{H,max}, \dot{Q}_{H,nominal}\right)$$

3.8 Loads on inside interfaces

Distribution of short wave radiation gains

Short wave radiation loads through windows are equally distributed using the same radiation intensity on all wall surfaces $q_{SWRad,W}$. The incoming solar heat gains through all windows $\sum_i^{n_F} \dot{Q}_{SWRad,i}$ partly heats up the room air directly (fraction of γ_{SWRad}) and acts directly on wall surfaces. The radiation intensity per square meter wall surface is then given by:

$$q_{SWRad,W} = \frac{(1 - \gamma_{SWRad}) \sum_i^{n_F} \dot{Q}_{SWRad,i}}{\sum_j A_{W,j}}$$

$\sum_j A_{W,j}$ denotes the sum of internal netto wall surfaces.

Distribution of radiant heating gains

Long wave radiation gains $\dot{Q}_{H,rad,i}$ are transferred between the heating and the wall surfaces and are provided explicitely by a heating element. In a similar manner to the short wave radiation gains, long wave radiation heat gains are distributed with a uniform heat flux density $q_{H,W}$ towards all wall surfaces.

$$q_{H,W} = \frac{\sum_i^{n_H} \dot{Q}_{H,rad,i}}{\sum_j A_{W,j}}$$

Distribution of radiant occupancy gains

Similarly, long wave radiation gains from persons, technical equipment and lighing $\dot{Q}_{k,rad}$ are uniformly distributed on all wall surface with the heat flux density $q_{k,W}$, where k represents persons (P), technical equipment (E) and/or lighting (L):

$$q_{k,W} = \frac{\dot{Q}_{k,rad}}{\sum_j A_{W,j}}$$

Long wave radiation exchange

If view factors between all inside wall and window surfaces are defined, long wave radiation exchange is activated. Using thermal equilibrium approach the emitted radiation $e_{W,i}$ is set equal to the adsorbed one and described by Stefan-Boltzmans law:

$$e_{W,i} = \varepsilon_{W,i}\sigma T_{W,i}^4$$

Radiosity $j_{W,i}$ of the surface includes emitted and backward reflected radiation. We describe the received radiation of the wall surface by irradiance $h_{W,i}$ and calculate the reflected amount of incoming radiation by $(1-\varepsilon_{W,i})\,h_{W,i}$:

$$j_{W,i} = e_{W,i} + (1-\varepsilon_{W,i})\,h_{W,i}$$

Incoming radiation is the sum of radiosity from all other visible surfaces. The visibility of the current surface to each other surface is described by the view factor $\Phi_{i,j}$:

$$h_{W,i} = \sum_{j\neq i}^{n_W} \Phi_{i,j} j_{W,j}$$

These equations forms a linear equation system with respect to the radiosities $j_{W,i}$. The long wave radiation gains towards each wall $q_{ex,W,i}$ result from the remaining difference of incoming and emitted radiation:

$$q_{ex,W,i} = h_{W,i} - j_{W,i}$$

Windows are considered as opaque and do not adsorb long wave radiation. Long wave emissivity of each window is set to $\varepsilon_{F,i}$ =0.

3.9 Evaluation of thermal comfort

The mean radiant temperature T_{rad} and the operative temperature T_{op} are accessable parameters for evaluation of thermal comfort. Approximately we use an area-weighted average of all wall and window inside surface temperatures with $\sum_i A_{W,i} + \sum_i A_{F,i}$ denoting the sum of all inside brutto surface areas (including the window areas). Operative temperature is considered as arithmetic mean of room air temperature T_R and radiant temperature T_{rad} .

$$T_{rad} = \frac{\sum_i A_{W,i} \cdot T_{W,i} + \sum_i A_{F,i} \cdot T_{F,i}}{\sum_i A_{W,i}}$$

$$T_{op} = \frac{T_R + T_{rad}}{2}$$

References

[1] NANDRAD data format. URL: https://141.30.43.38/Nandrad/wiki/FileProjectFile. 1

[2] A. Nicolai. Physikalische Grundlagen des thermischen Raummodells THERAKLES, 2013. URL: http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-102112. 1

[3] A. Nicolai. Physical reference of the climate calculation module, 2017. in prep. 2.4, 3.5