Numerical Analysis of Comfort and Energy Performance of Radiant Heat Emission Systems

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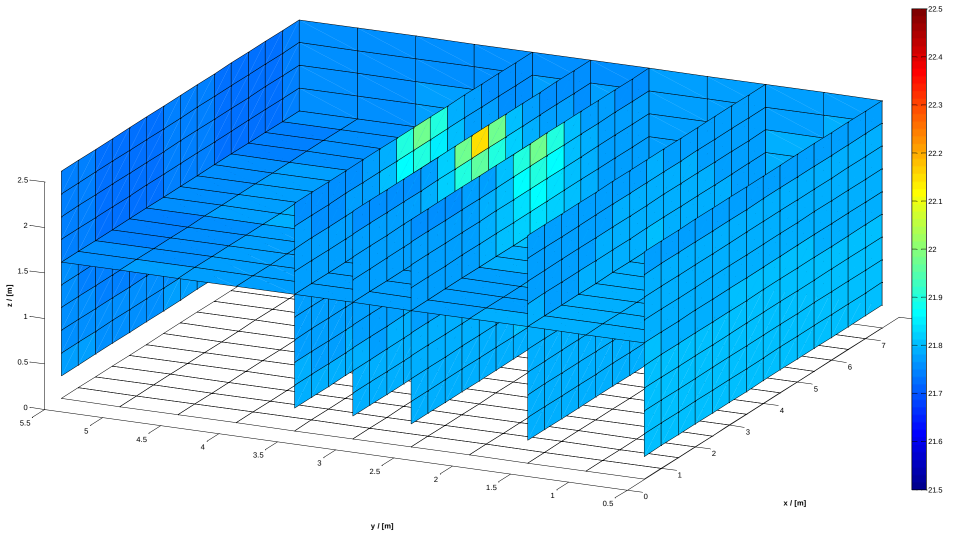


Comsol Conference, 2016, Munich

Motivation

Recently so-called **infrared-heating systems** are increasingly discussed as a cost-effective heating system.

Relative small areas of typically 0.6 m x 1.2 m with high surface **temperatures of up to 120 °C** are used.

Definition:
With a radiant heating system more than 50 % of heat emission occurs as long-wave radiation (infrared)

Questions …

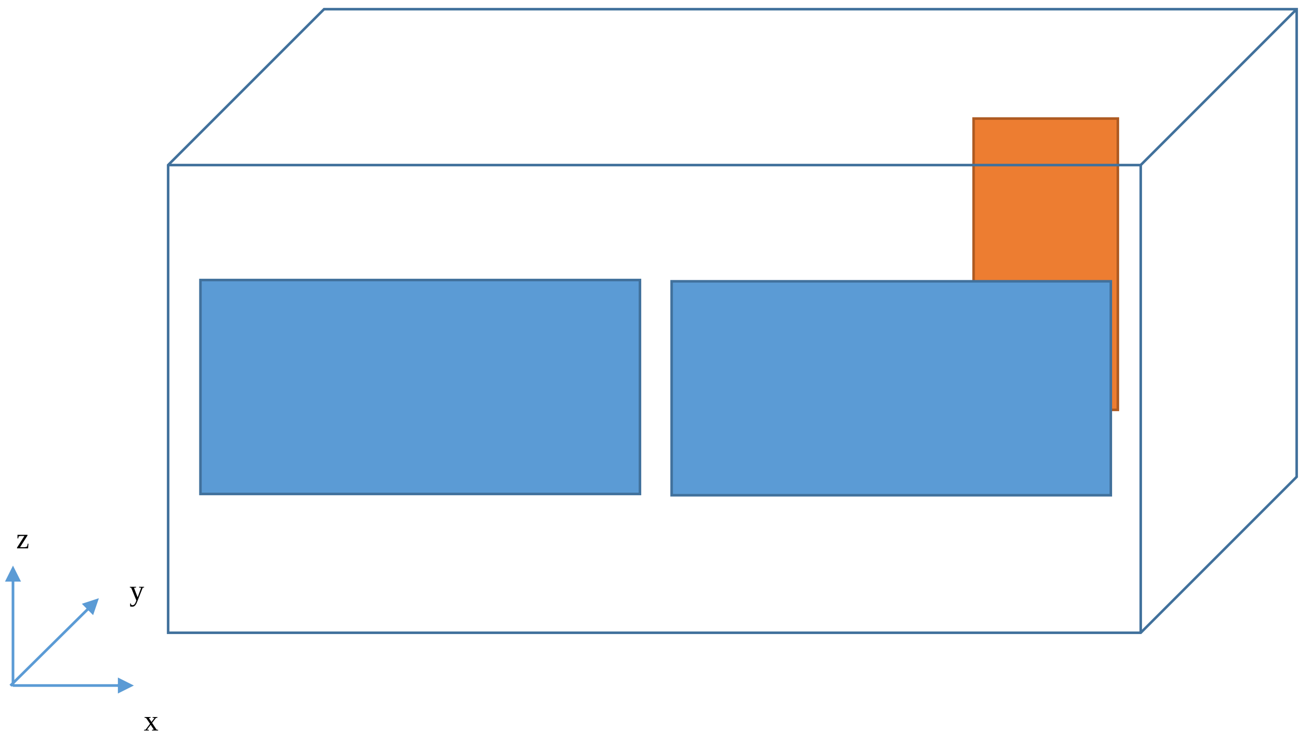
- What is the **appropriate dimensioning** of the radiant system depending on the load of the building?
- What are the **comfort conditions** with radiant heating systems and how should they be determined and evaluated?
- What is the **energy performance** compared to reference systems such as hydronic heat emission systems e.g. with air-sourced heat pump?
- Is there a benefit in intermittent operation due to the relative fast response of these heating systems?

Scheme of simple 3D Room Model (shoe-box)

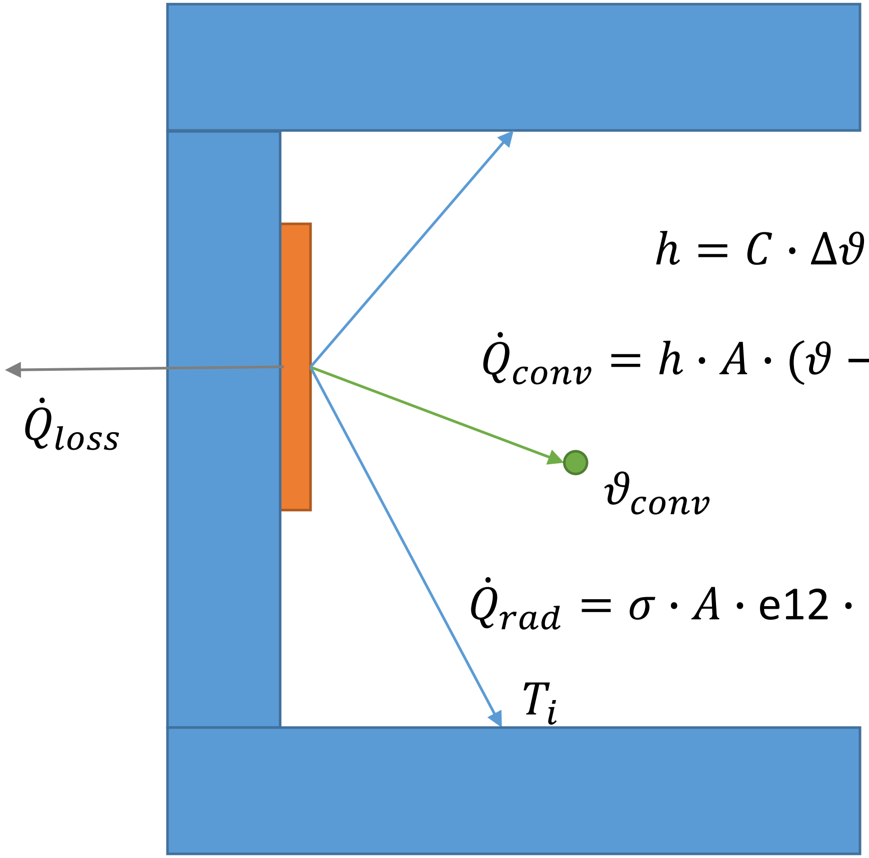
Variation of
- size and
- position of the radiant heater
- window fraction
- envelope quality

Comparison with heating demand in case of convective heating

Control according to the operative temperature



Simplified Model of a Radiative Heater



$$h = C \cdot \Delta\vartheta^n$$

$$\dot{Q}_{conv} = h \cdot A \cdot (\vartheta - \vartheta_{\mathrm{conv}})$$

$$\dot{Q}_{rad} = \sigma \cdot A \cdot \mathrm{e12} \cdot (\mathrm{T}^4 - \mathrm{T_i}^4)$$

$$\dot{Q}_{tot} = \dot{Q}_{rad} + \dot{Q}_{conv} = P = U \cdot I$$

Assumption 1:
Grey (i.e. diffuse) radiator

- Homogeneous temperature (ϑ_R)
- Homogenous emissivity (ε) of each surface

Assumption 2:
$\dot{Q}_{loss} = 0$

Thermal Comfort - Operative Temperature

- Operative Temperature (approximation)

$$\vartheta_{op} = \frac{\vartheta_{rad}+\vartheta_{conv}}{2}$$

ϑ_{rad}: radiative Node

- Operative Temperature (improved approach)

$$\vartheta_{op} = (1-a) \cdot \vartheta_{rad} + a \cdot \vartheta_{conv} \qquad a = \frac{h_C}{h_C + h_R}$$

here: 0.35 < a < 0.5

ConveCtive heat transfer coefficient $h_C = 1.4 \cdot ((\vartheta_{conv} - \vartheta_s)/D)^{1/4}$

Radiative heat transfer coefficient $h_R = \sigma \cdot e \cdot (\vartheta_s + \vartheta_{rad}) \cdot (\vartheta_s^2 + \vartheta_{rad}^2)$

Thermal Comfort - Radiant Temperature Asymmetry

- Asymmetric heating or cooling of a human due to different radiant temperatures of the surrounding surfaces can lead to dis-comfort.
- The room is divided into two half-rooms for the evaluation of the radiant temperature asymmetry. The temperature differences between the two half-rooms should not exceed certain values.

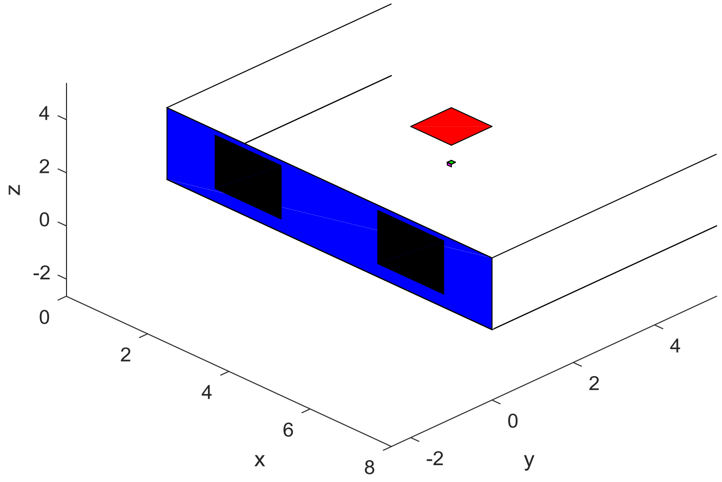


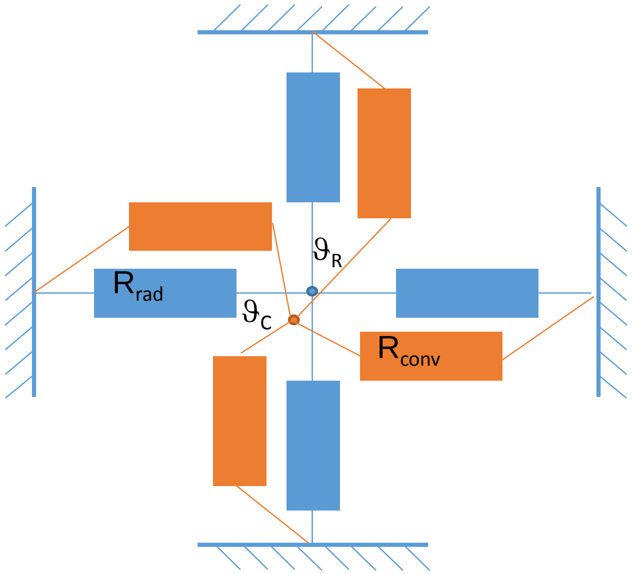
Table: Maximum Radiant Temperature Asymmetry

	DIN 1946-2	ISO 7730	Glück
Warm ceiling	3.5 K	5 K	8.1 K
Cold wall	8 K	10 K	8.4 K
Cold ceiling	17 K	14 K	14.3 K
Warm wall	19 K	23 K	11.1 K

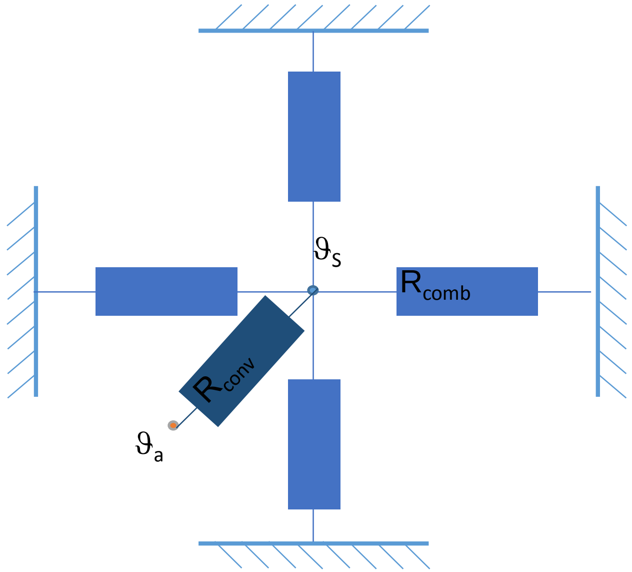
Building Models

- 1-Zone 2* Modell (convective and radiative node)
- 1-Zone Model with detailed physical radiation approach

Simpliefied Building Model Approaches



2 * model

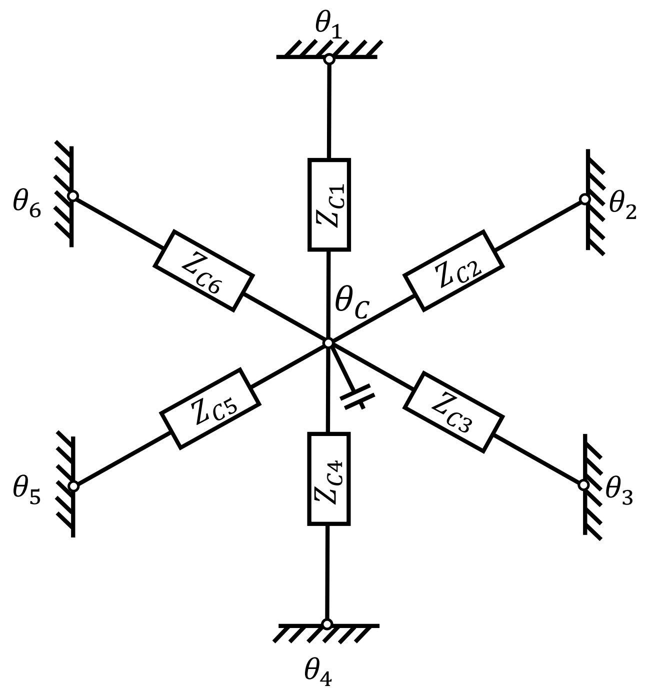


2 starnode model

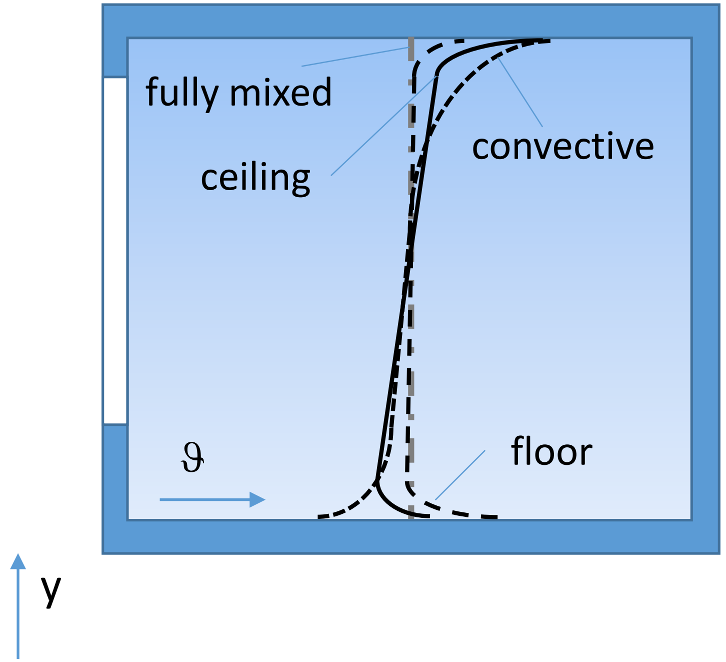
z.B. Dynbil, Matlab/Simulink, Energy+

z.B. EN ISO 13970, TRNSYS, Energy+

Physical Model - Convective Node



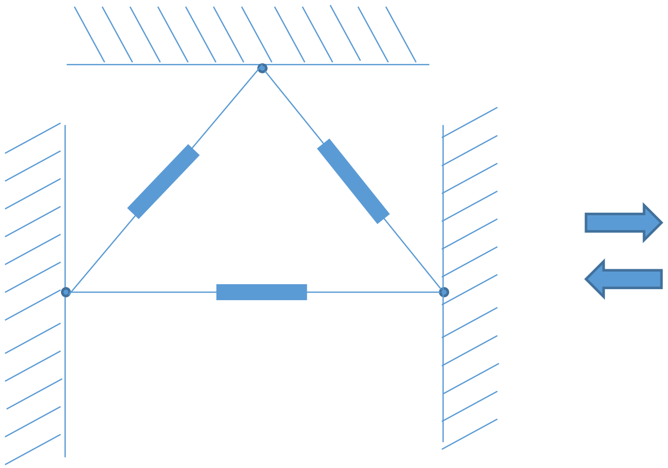
Modell for convective heat transfer (6 surfaces)



Temperature Stratification in a room for different heating situations

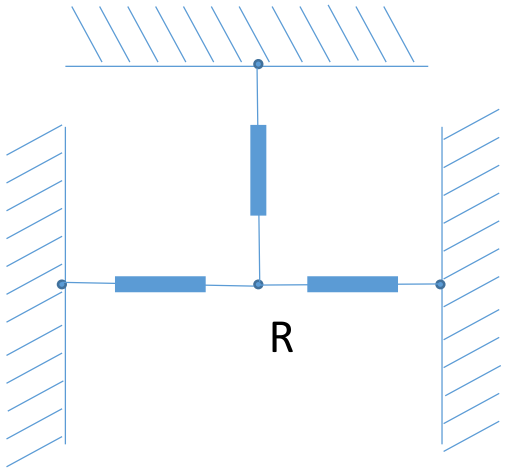
Remark: Ideally mixed room applies with good approximation for buildings with very good envelope quality (PH). For a more accurate analysis, in addition, a computational flow simulation (CFD) for determining the temperature stratification would be needed.

Models for Radiation Heat Transfer



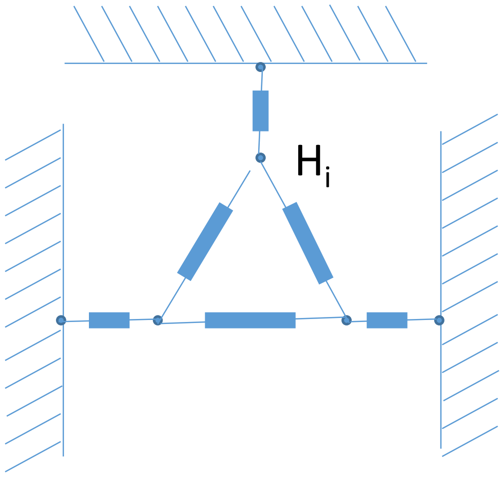
Triangle-Configuration
(black body)

$$\dot{Q}_{ij} = \sigma \cdot A_i \cdot e_i \cdot e_j \cdot F_{ij} \cdot (T_i^4 - T_j^4)$$



Star-Configuration

$$\dot{Q}_{iR} = \sigma \cdot A_i \cdot e_i \cdot e_R \cdot F_i \cdot (T_i^4 - T_R^4)$$



Physical Model with Radiosity H
(Grey body)

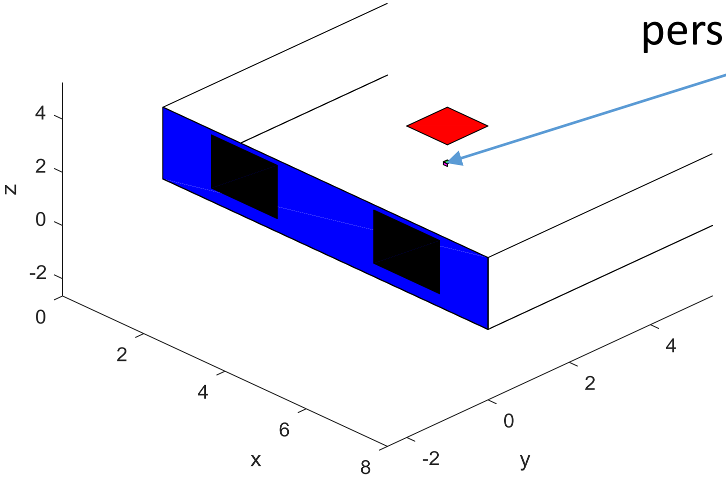
$$H_i = \epsilon_i \cdot \sigma \cdot T_i^4 + (1 - \epsilon_i) \cdot \sum_{j=1}^{n} F_{ij} \cdot H_j$$

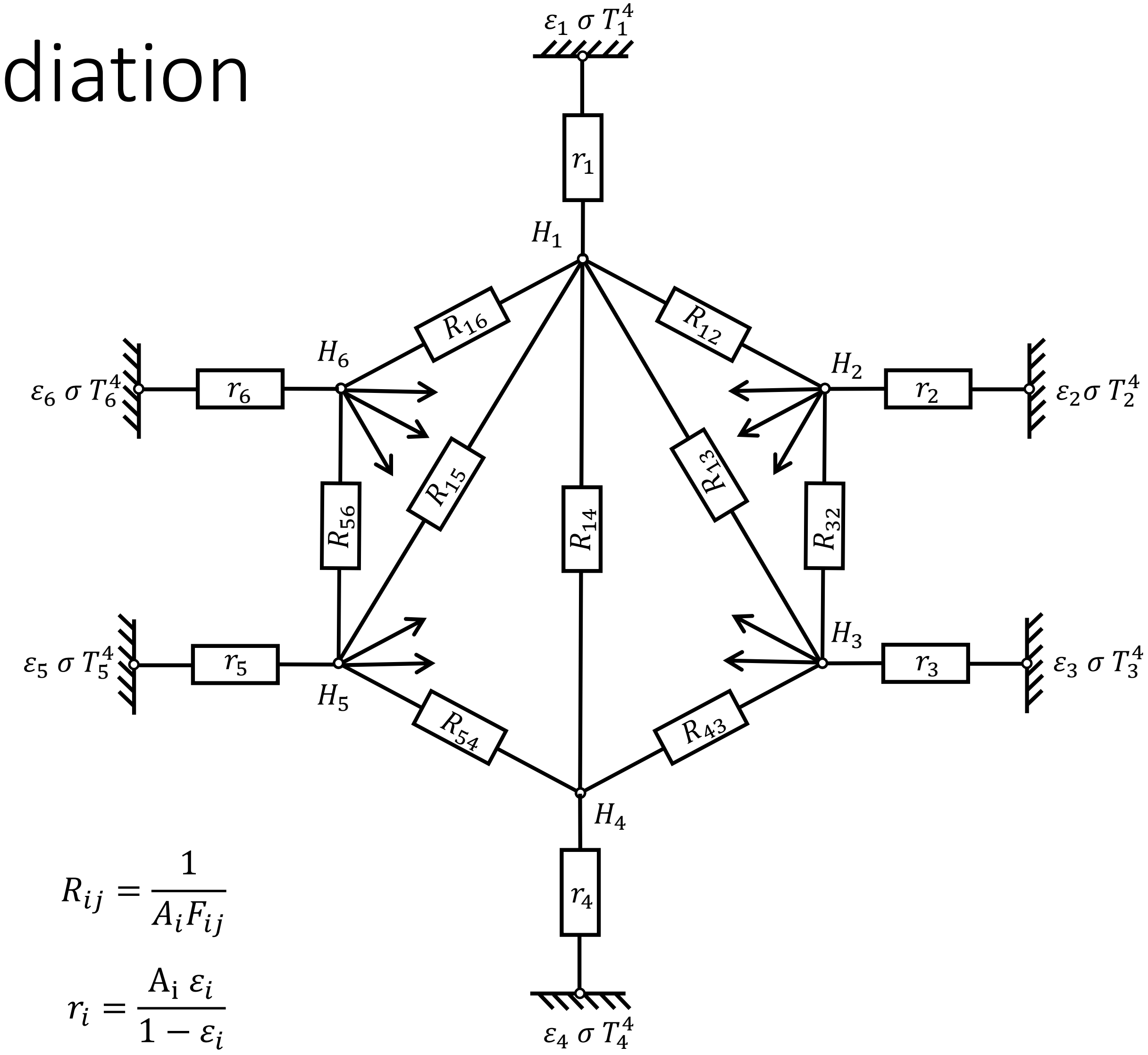
$$\dot{Q}_i = A_i \cdot \sum_{j=1}^{n} (\delta_{ij} - F_{ij}) \cdot H_j$$

Physical Room Model - Radiation

- View factors depend only on geometry
- Not on surface properties.

Sphere o cube representing a person

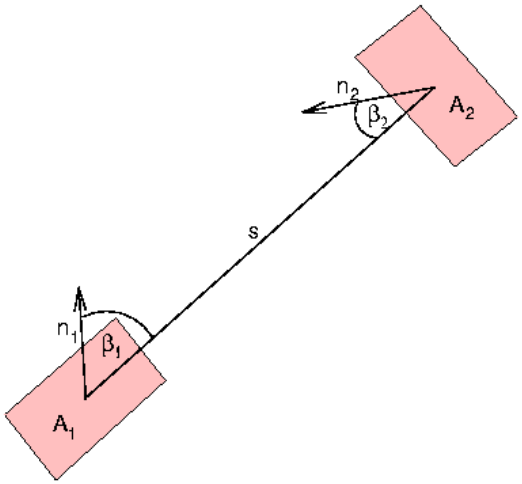




$$R_{ij} = \frac{1}{A_i F_{ij}}$$

$$r_i = \frac{\mathrm{A_i}\ \varepsilon_i}{1 - \varepsilon_i}$$

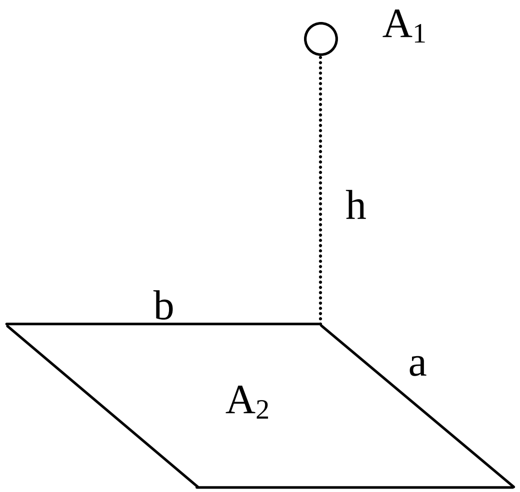
View factor



- Determination by means of integration
  - analytically
  - Numerical integration
    - with Comsol Multiphysics

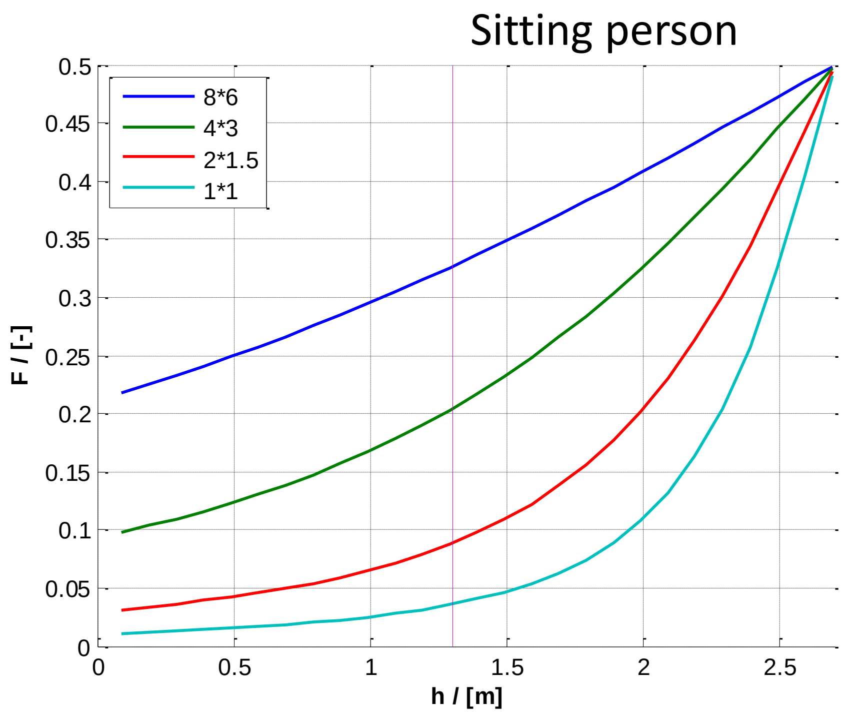
$$F_{12} = \frac{1}{\pi A_1} \iint_{A_1 A_2} \frac{\cos\beta_1 \cos\beta_2}{r^2} dA_1 dA_2$$

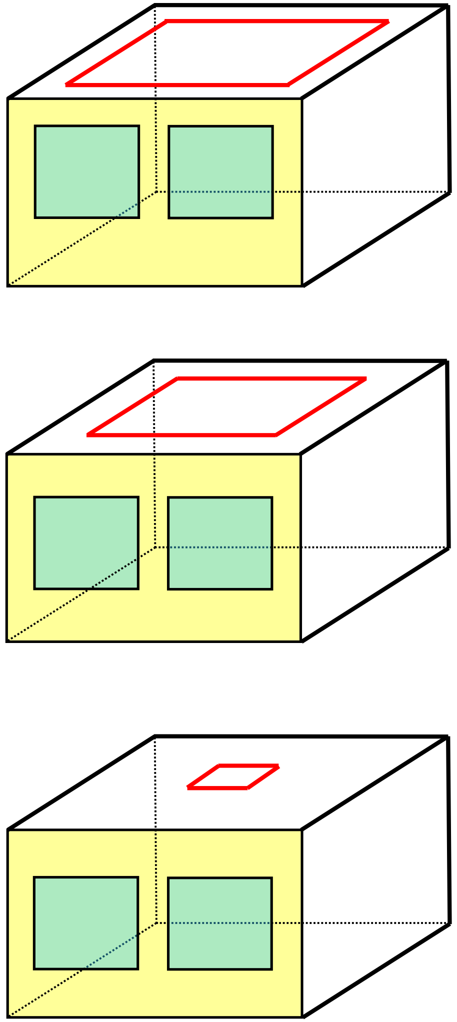
$$F_{1,2} = \frac{1}{8} - \frac{1}{4\pi} \arctan \sqrt{\frac{1+(a/h)^2+(b/h)^2}{(a/h)^2 \cdot (b/h)^2}}$$



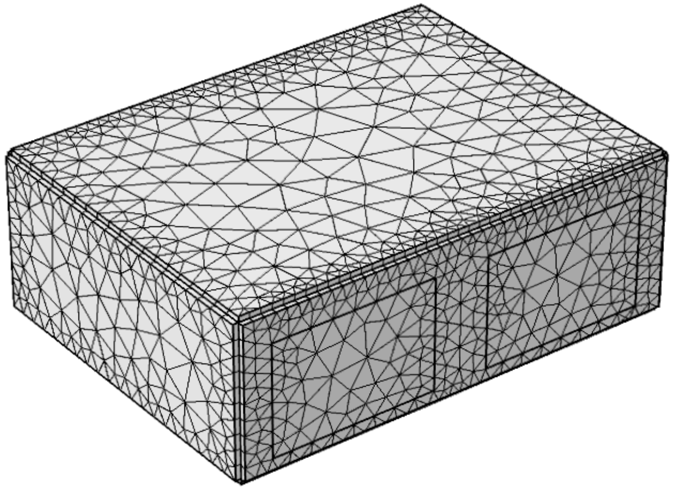
View Factor

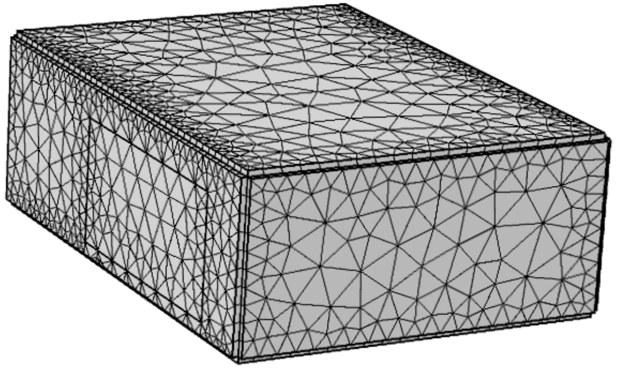
View factor between heater and sphere in the center of the room depending on the distance (h) to the heater





3D-Model in Comsol® (FE-Modell)





- Determination of view factor from surface to surface
  9 x 9

- Determination on view factor from sphere in room to the surrounding surfaces
  9 per each position (x,y,z) in the room

View Factor Calculation in Comsol®

Radiosity approach with the irradiation G (here G is the mutual irradiation coming from the other boundaries), the radiosity H and the emissivity ε:

$$(1-\varepsilon)\cdot G = H - \varepsilon \cdot \sigma \cdot T^4$$

- Surface to surface radiation physics, where it is necessary to run one simulation for every view factor which has to be calculated. The COMSOL® operators radopd(H_{up}, H_{down}) and radopu(H_{up}, H_{down}) are used.
- Heat Transfer with Surface-to-Surface Radiation physics where surfaces are presented as solid objects.

$$H_i = -\dot{Q}_i \frac{(1-\varepsilon_i)}{\varepsilon_i A_i} + \sigma \cdot T_i^4$$

View Factor Calculation in Comsol®

- The emissivity can be a function of wavelength (λ) and surface temperature (T).
- Complex geometries also with obstructions can be considered.
- However, the hypothesis of diffuse grey surface has to hold i.e. every surface has the absorption coefficient equal to the emissivity coefficient and emissivity and absorptivity are independent of the angle of emission or absorption, respectively.

Positionen and Size of Radiant Heater

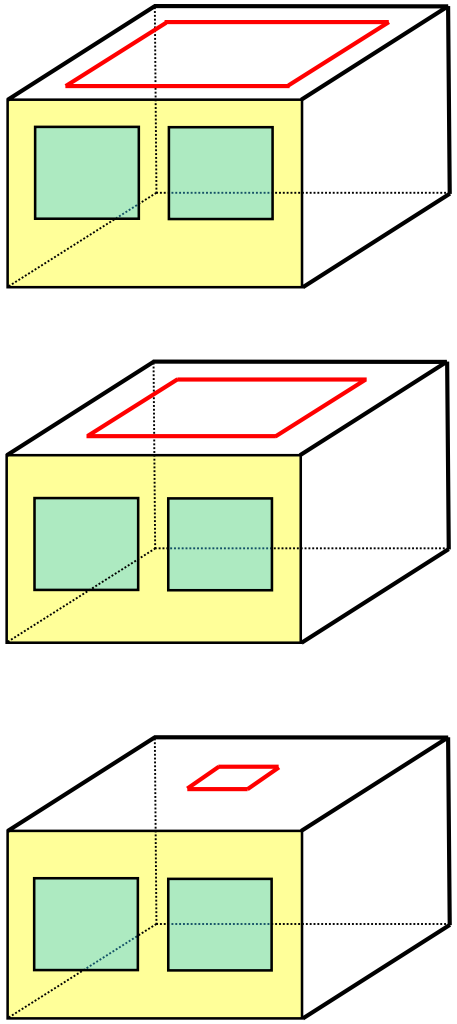
Position

- Ceiling
- Floor
- Side wall
- Rear wall

Size

- 1 m² (Small)
- Medium
- Large

Room Dimensions:
L x B x H [m]
8 x 6 x 2.7
Window fraction
30 % and 60 %

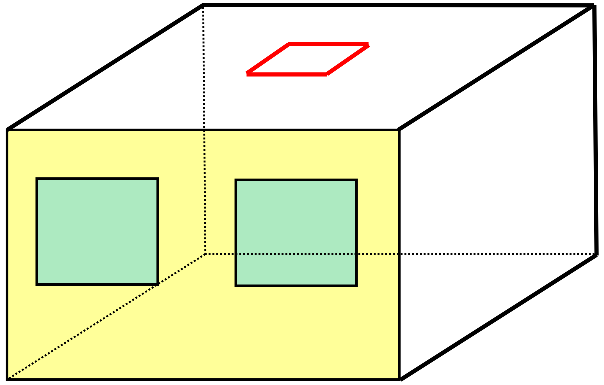


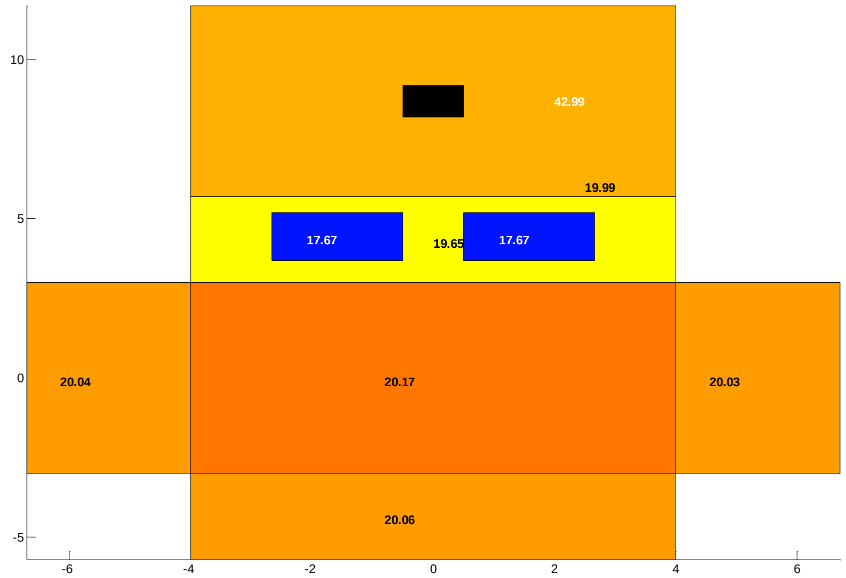
Matrix of investigated cases

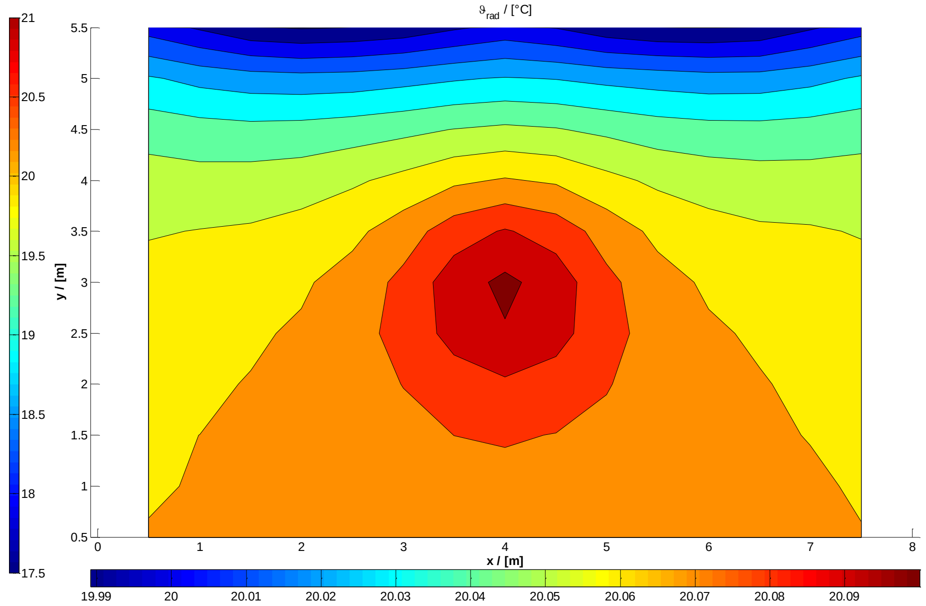
		Position of the heater			
		Rear wall (3)	Floor (5)	Ceiling (6)	Side wall (4 or 2)
Size of the heater	Small (1m x 1m)	X		X	X
	Medium 50% wall area	X	X	X	X
	Large 90% wall area	X	X		X

STEADY STATE: ceiling small W30 centered

Operative Temperature = 20°C
Qdot_tot = 206.77 W
Temperature Heater = 42.99 °C
Radiative exchange Heater = 67.78 %

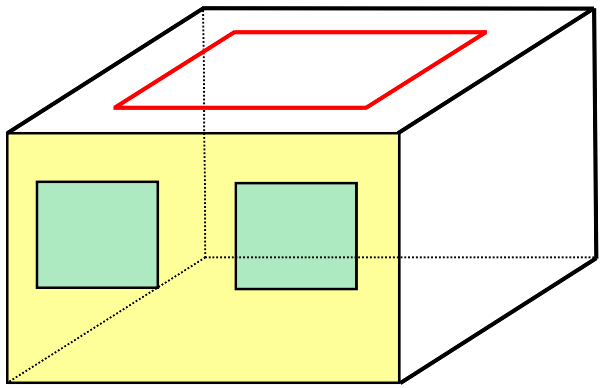


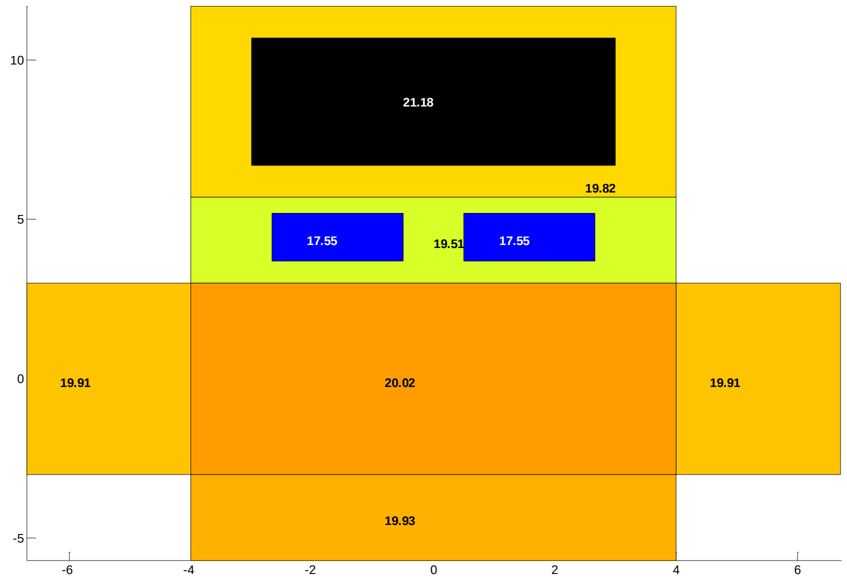


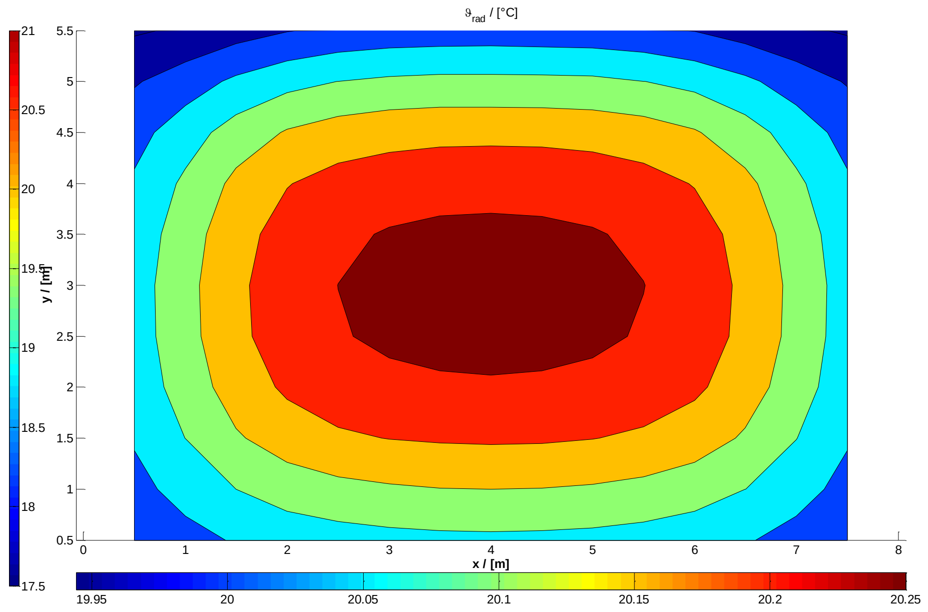


STEADY STATE: ceiling medium W30 centered

Operative Temperature = 20°C
Qdot_tot = 205.02 W
Temperature Heater = 21.18 °C
Radiative exchange Heater = 84.10 %

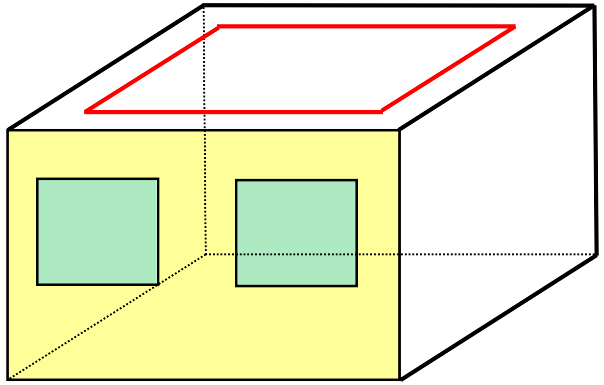


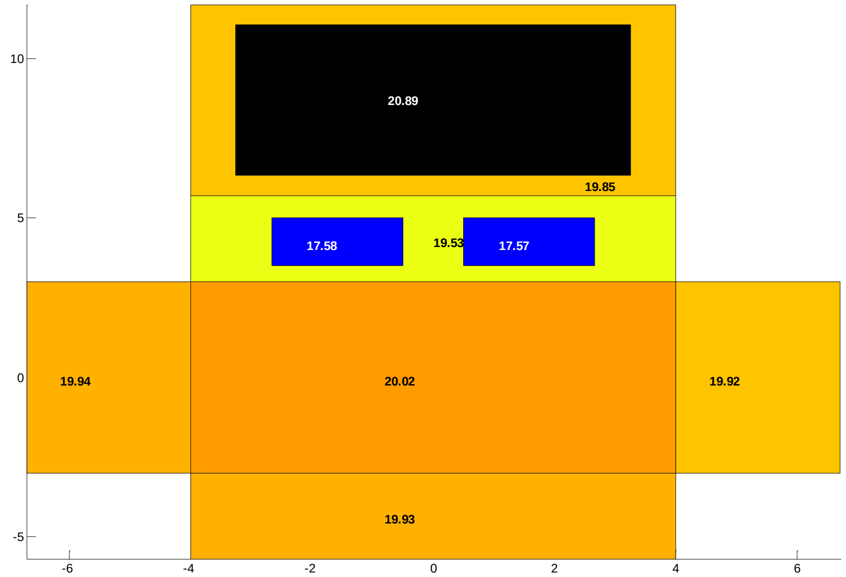


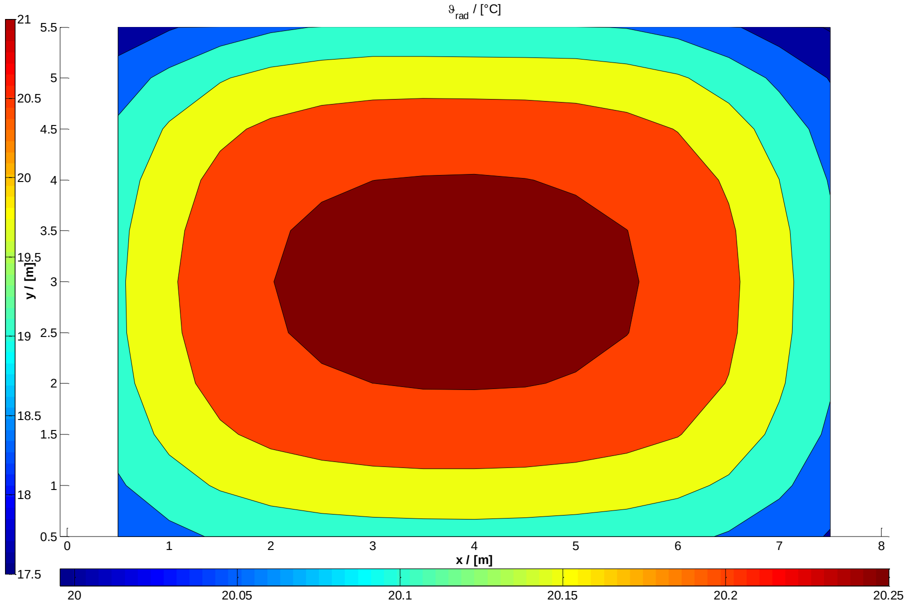


STEADY STATE: ceiling large W30 centered

Operative Temperature = 20°C
Qdot_tot = 205.21 W
Temperature Heater = 20.89 °C
Radiative exchange Heater = 84.82 %

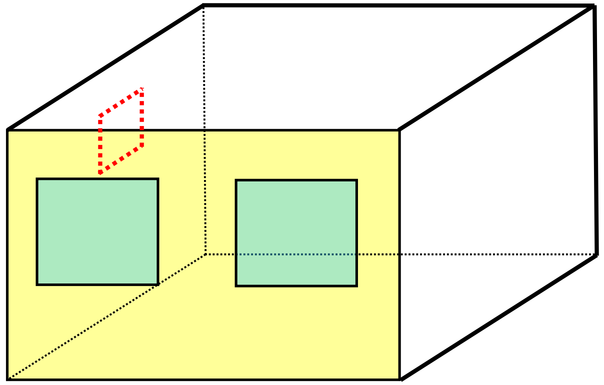


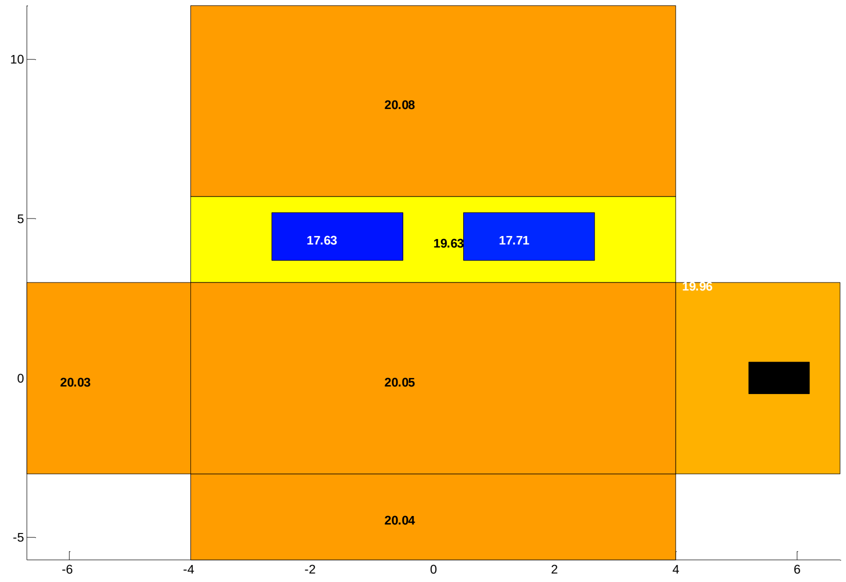


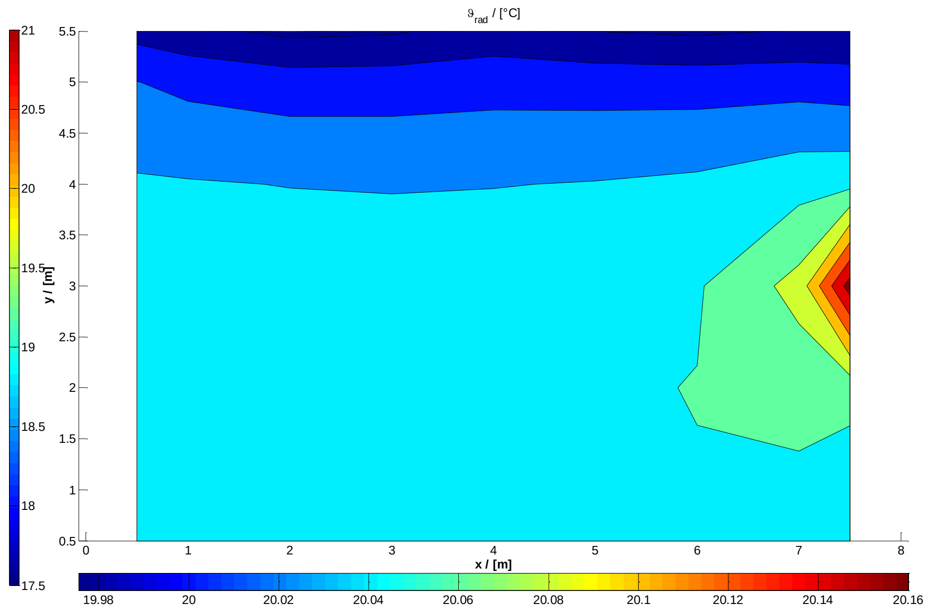


STEADY STATE: sidewall small W30 centered

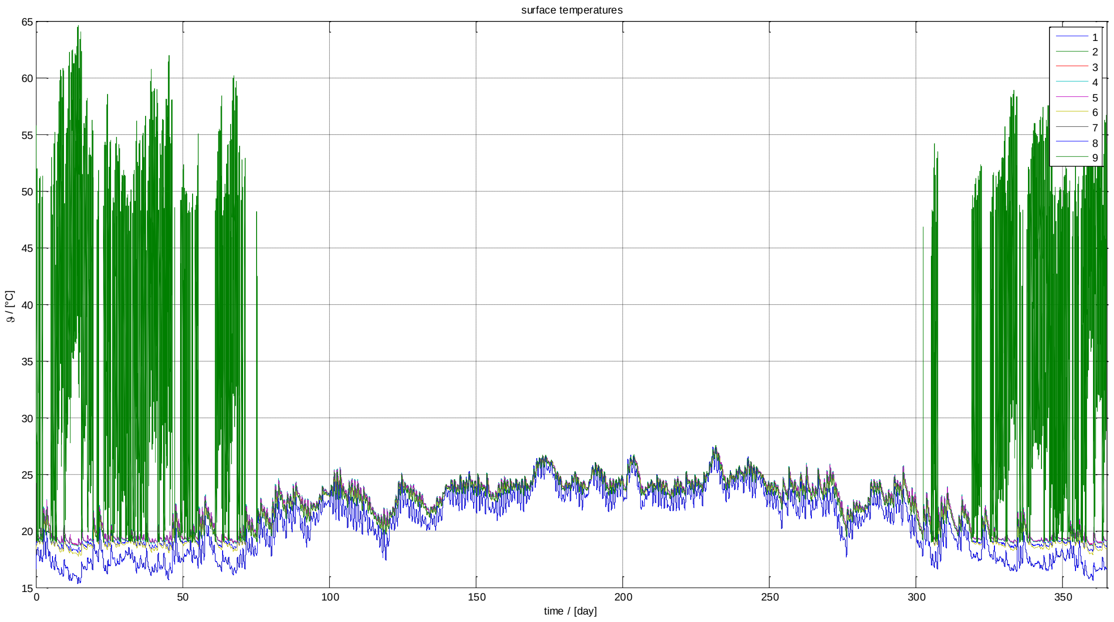
Operative Temperature = 20°C
Qdot_tot = 206.97 W
Temperature Heater = 39.85 °C
Radiative exchange Heater = 57.70 %

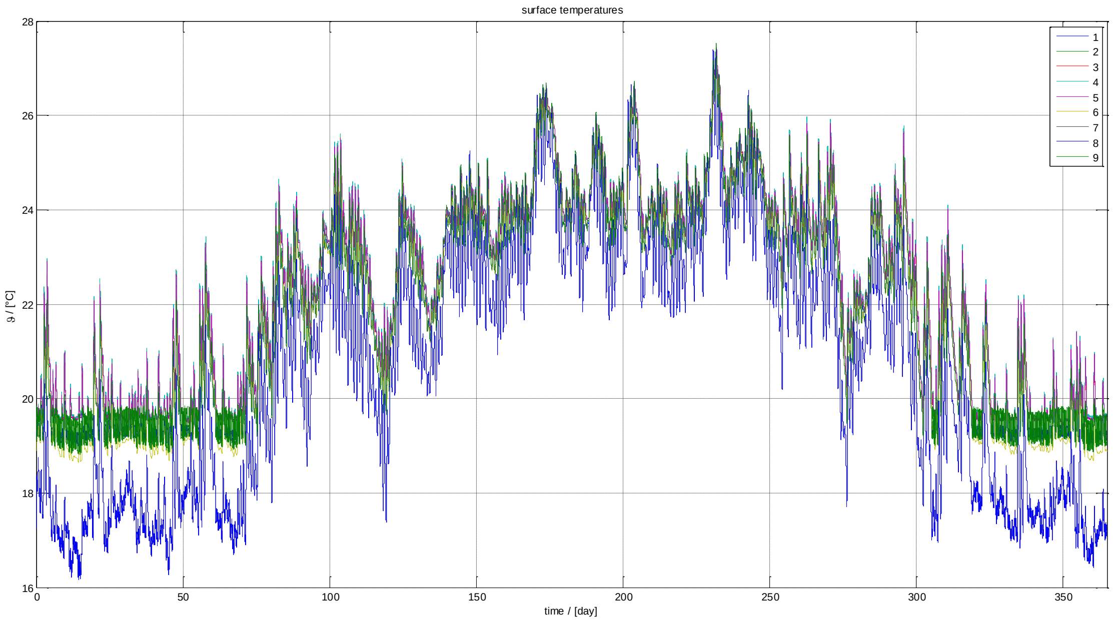






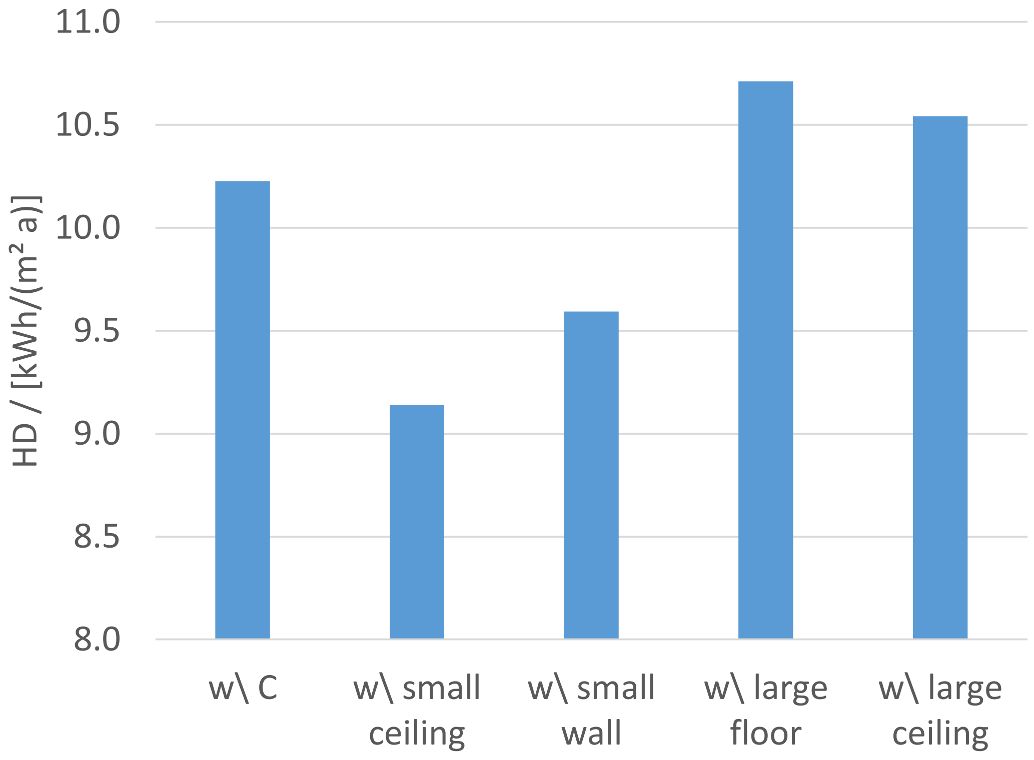
Transient Simulations





Example of Surface temperature with (left) radiative heater and (right) convective heating

Convective vs. Radiative Heating for Different Positions and Sizes of the Radiative Heater



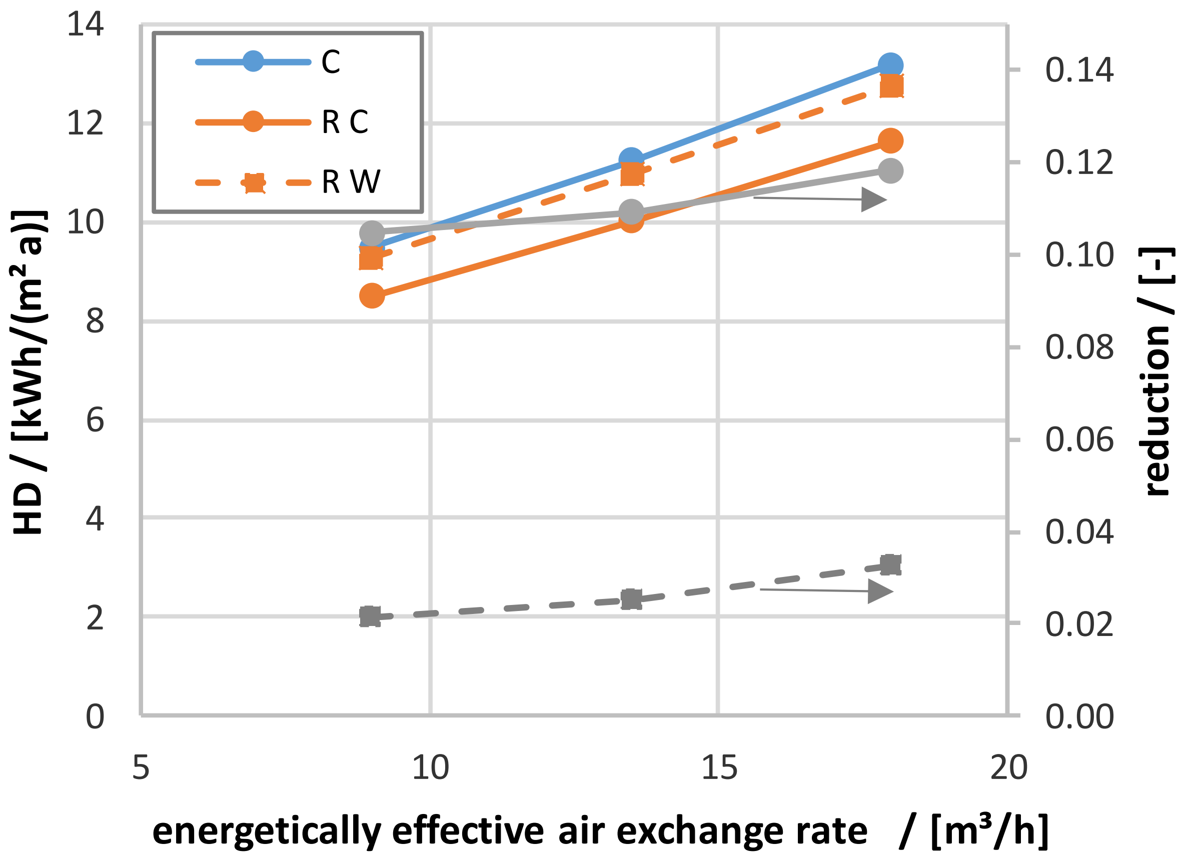
Innsbruck, 60 m³/h with MVHR

- For small radiative heating surfaces local comfort can be provided with leads to minor reduction of the heating demand (ca. 5 % for wall and 10 % for ceiling mounted systems (remark: violation of the comfort conditions with regard to the maximum radiant temperature asymmetry)
- Large radiant surfaces have higher heating demand than convective heating

Energetically effective Air Exchange Rate

Heating demand (HD) for the small radiative heater on the ceiling (R C) and wall (R W) and reduction with respect to convective heating (C) depending on the energetically effective air exchange rate

$n_{eff} = n\,(1-\eta) + n_{inf}$



Remark: With small radiant heater the radiant temperature asymmetry can exceed the limit according to ISO 3370

Conclusions – Radiant vs. Convective Heating

Radiant Heaters

- increase the radiant, i.e. surface temperature
- Allow to decrease the convective temperature for the same comfort conditions (operative temperature)

Hence, there are with radiant heaters

- (slightly) increased transmission losses
- (slightly) decreased ventilation losses

For the same temporal and spatial comfort, no significant differences between a predominantly convective heat emission system and one which emits predominantly long-wave radiation can be determined within the model accuracy.

Conclusion - Local Comfort

- If comfort is only defined for the occupied space, i.e. traffic area (in the same way as in case of ventilation on demand indoor air quality is defined only during presence i.e. there is no loss of comfort with regard to the temporal and local presence of the user), a low energy saving can be achieved without loss of comfort (i.e. with local comfort).
- It must be noted that the potential to create thermal comfort only locally is greater for small (and consequently hot) areas while however, the radiant temperature asymmetry in this case can even exceed the limit defined in ISO 7730.

Conclusion Building Modell

- In order to compute the differences of a heat emission system, which is predominantly convective or predominantly radiative with sufficient accuracy, a building model with a detailed calculation of the radiation exchange (between each of the surrounding areas, as well as between the surrounding surfaces and a sphere that is used for calculating the operative temperature) is required.
- With such a model, these effects can be figured out more precisely than with a two-star or star node model, as usually used for building simulations.
- The assumption of an ideal mixing of air is acceptable in rooms with very good insulation level and mechanical ventilation with heat recovery, however, it does not apply in case of radiative ceiling and/or ventilation without heat recovery. A computational flow simulation (CFD) for determining the temperature stratification would be required additionally for a more accurate analysis.

Outlook

A) Dimensioning Tool

B) Complex Geometries

C) Coupled CFD and Radation Exchange Model

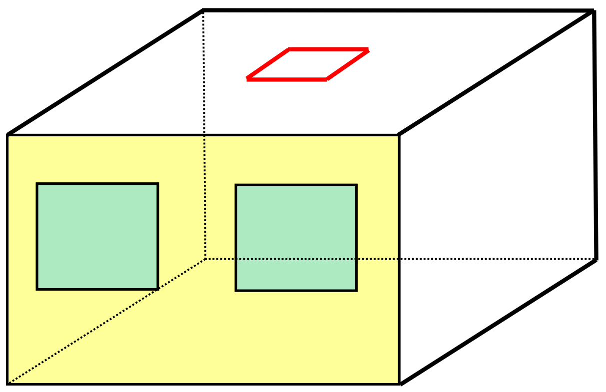
Acknowledgements

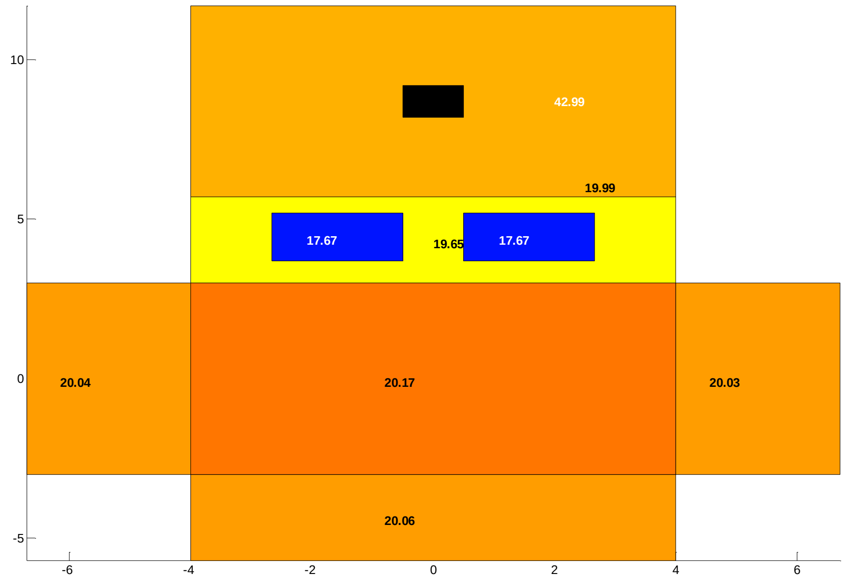
IFI Institut für Infrarotwärme GmbH initiated this work. The authors thank IFI Institut für Infrarotwärme GmbH for this initiative and for their support. For part of this work financial support was provided by the Austrian research funding association (FFG) under the scope of "Innovationscheck Plus".

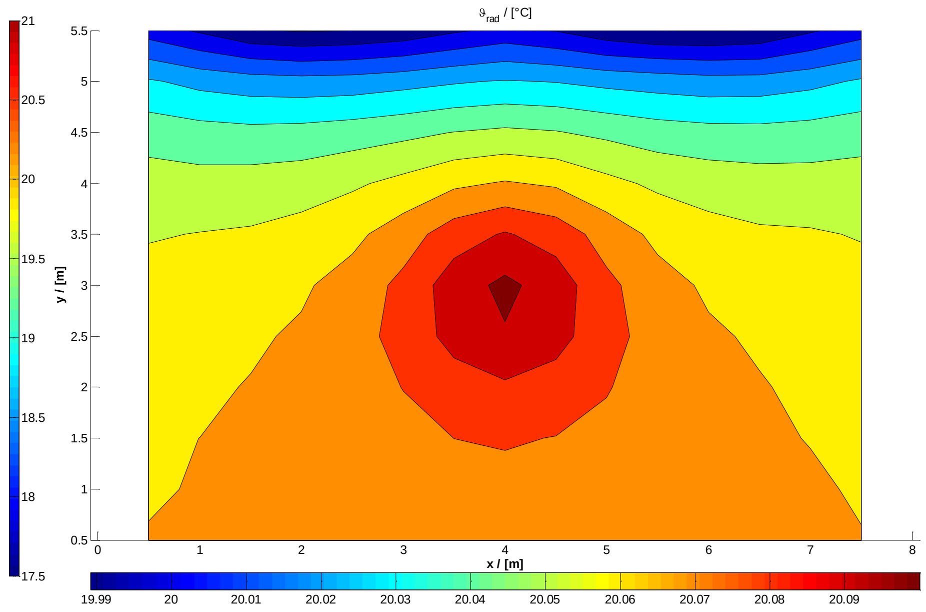
Thanks ….

STEADY STATE: ceiling small W30 centered

Operative Temperature = 20°C
Qdot_tot = 206.77 W
Temperature Heater = 42.99 °C
Radiative exchange Heater = 67.78 %







STEADY STATE: ceiling medium W30 centered

Operative Temperature = 20°C
Qdot_tot = 205.02 W
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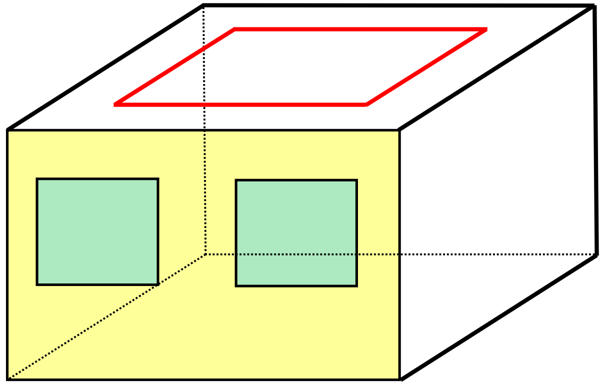

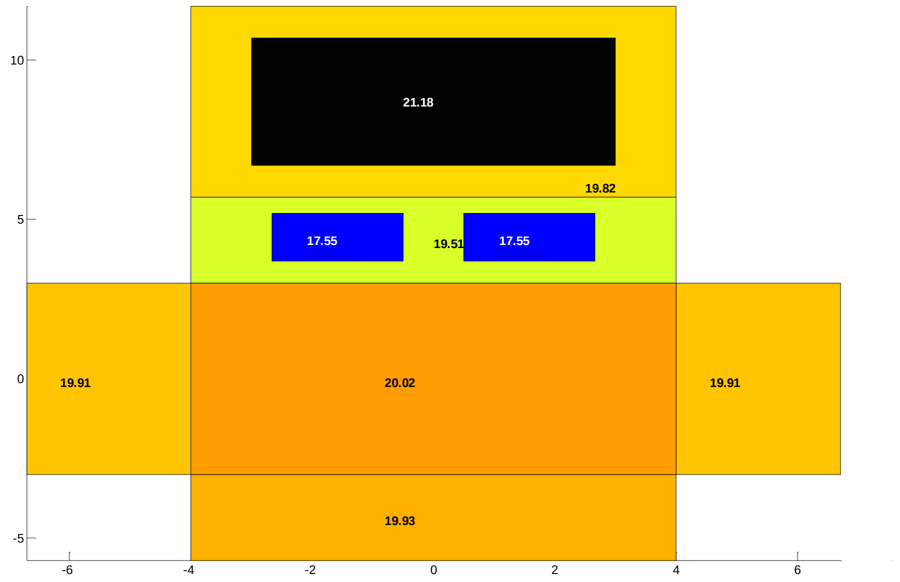

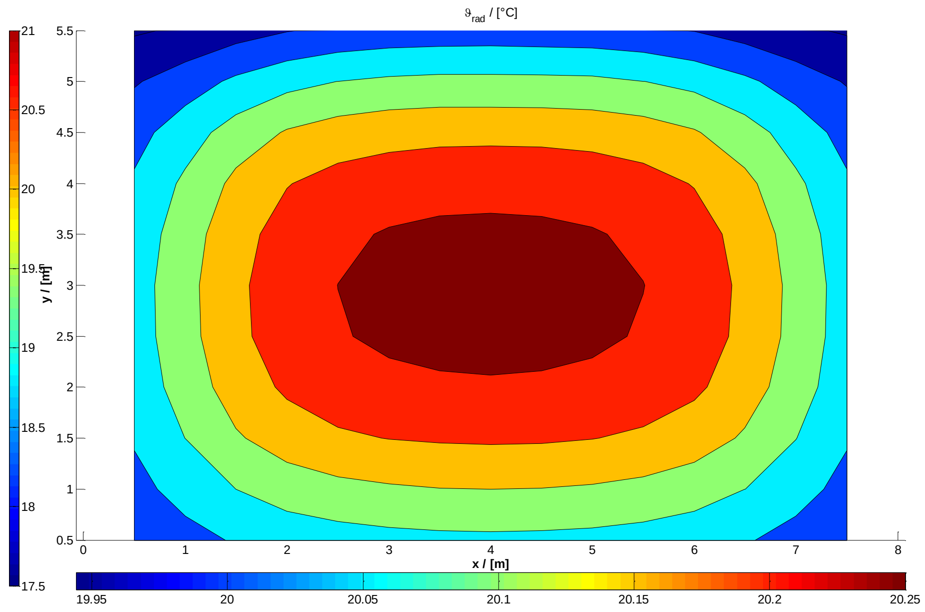

STEADY STATE: ceiling large W30 centered

Operative Temperature = 20°C
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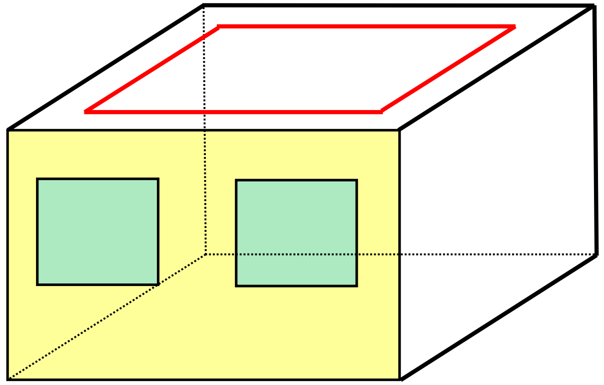
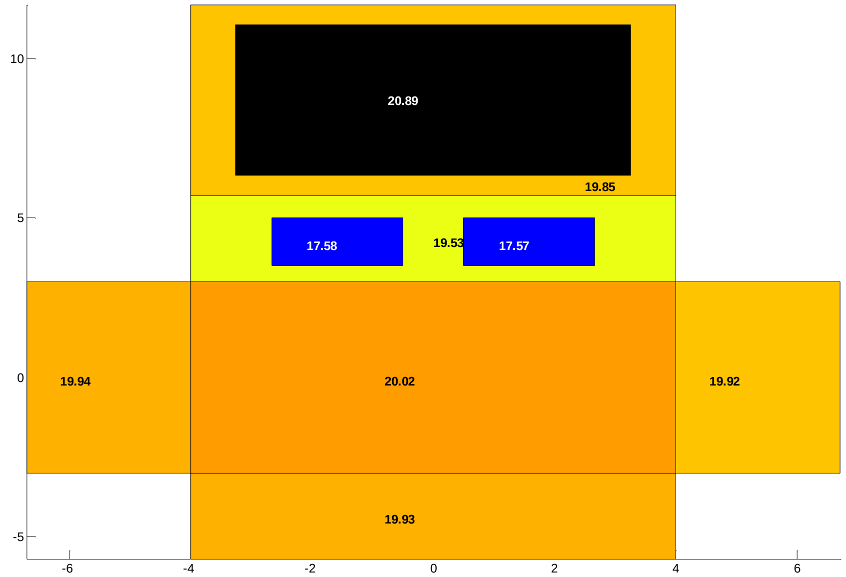
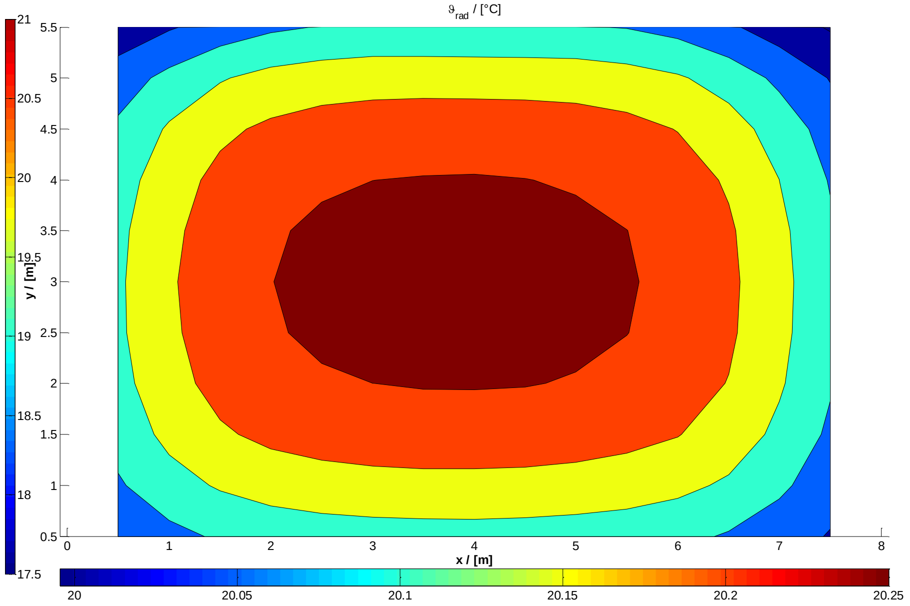
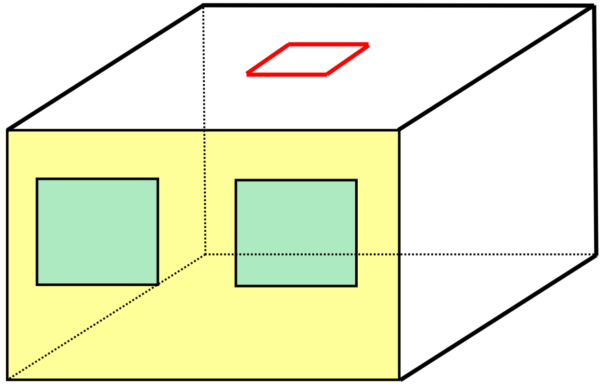


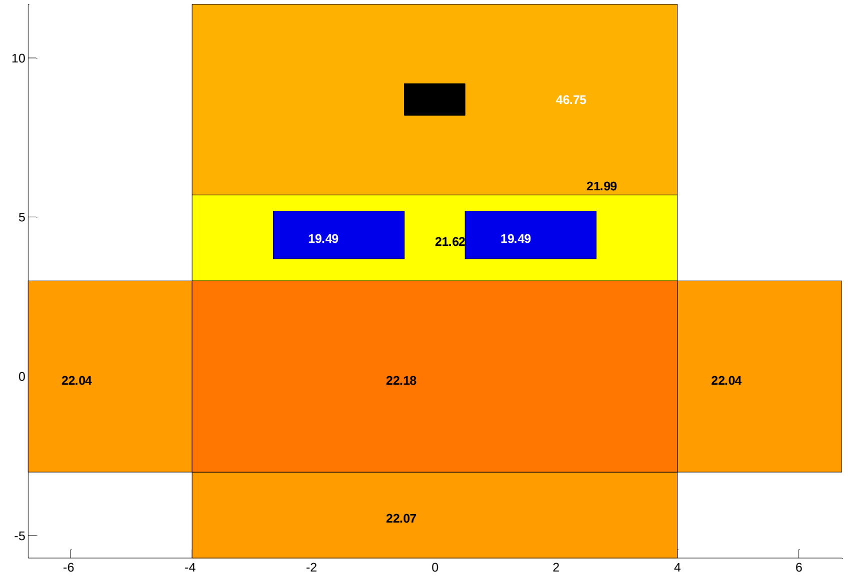


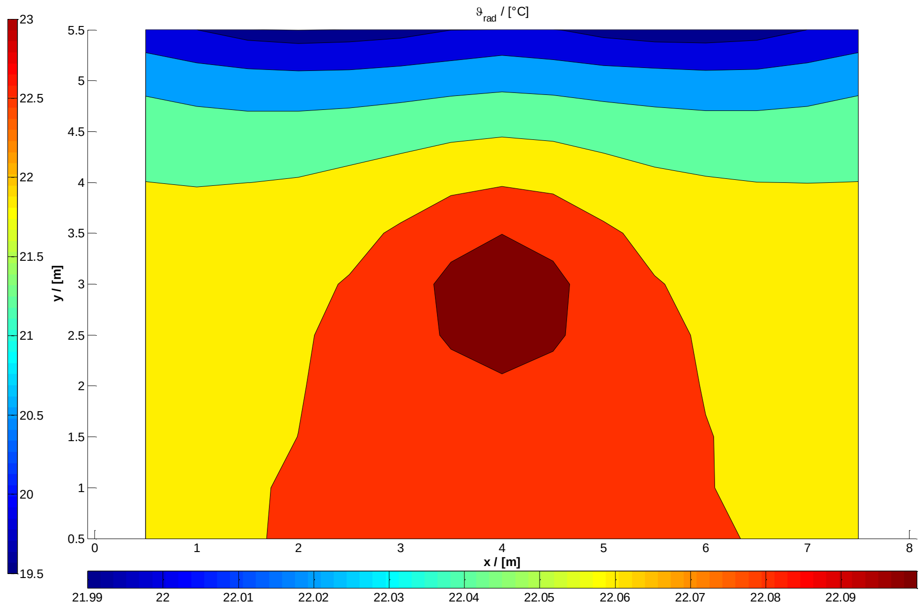


STEADY STATE: ceiling small W30 centered

Operative Temperature = 22°C
Qdot_tot = 227.75 W
Temperature Heater = 46.75 °C
Radiative exchange Heater = 68.13 %

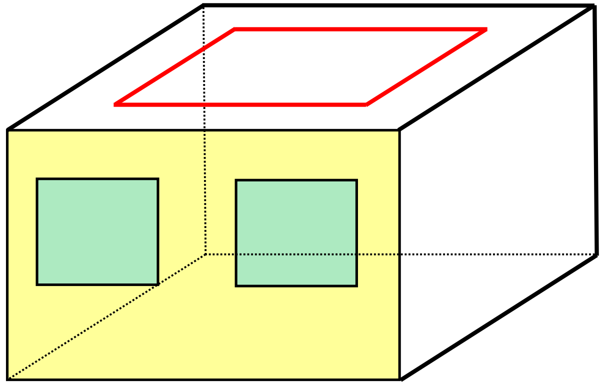


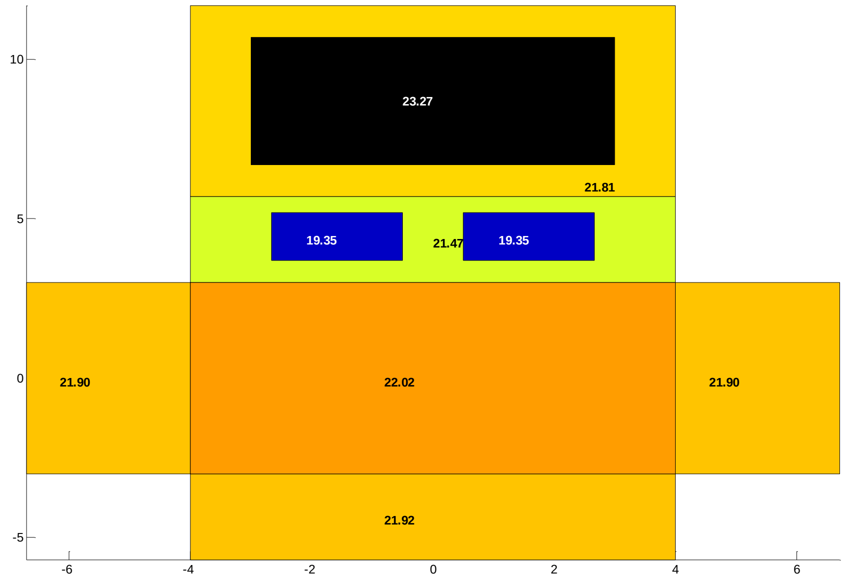


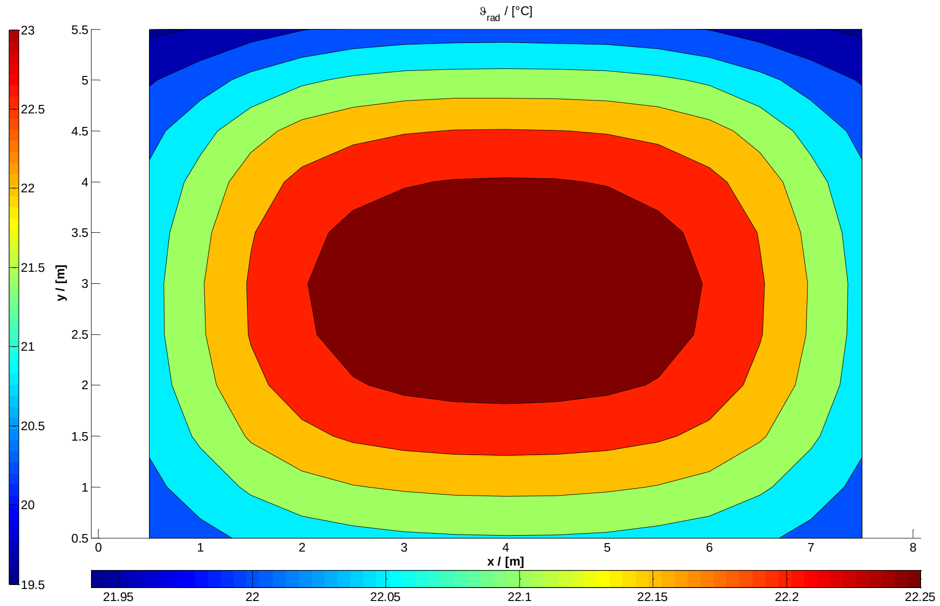


STEADY STATE: ceiling medium W30 centered

Operative Temperature = 22°C
Qdot_tot = 225.85 W
Temperature Heater = 23.27 °C
Radiative exchange Heater = 84.21 %

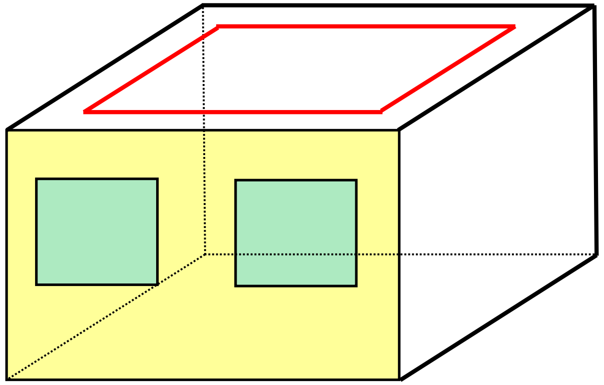


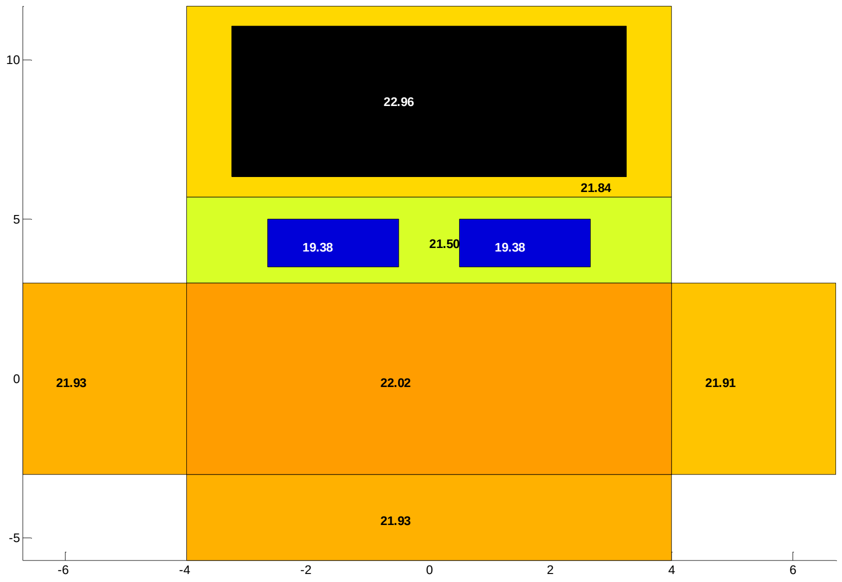


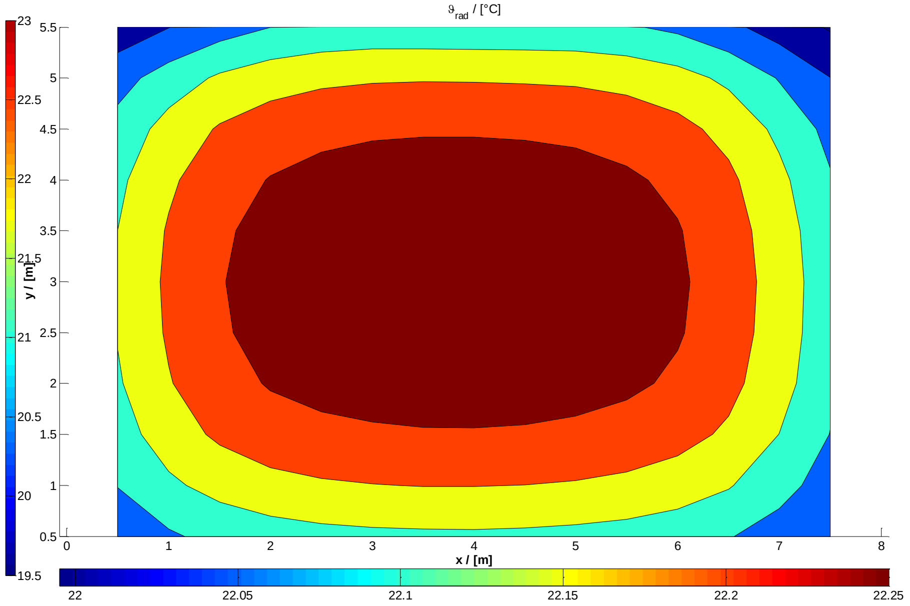


STEADY STATE: ceiling large W30 centered

Operative Temperature = 22°C
Qdot_tot = 226.06 W
Temperature Heater = 22.96 °C
Radiative exchange Heater = 84.93 %

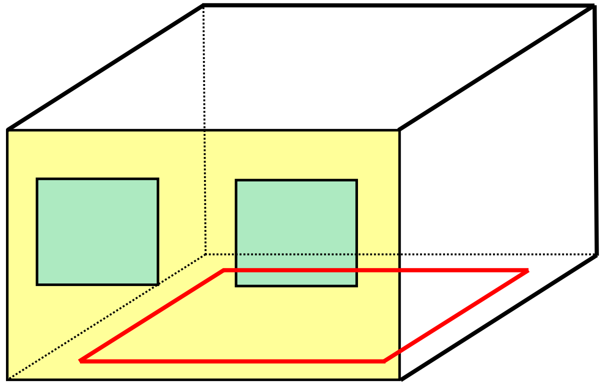


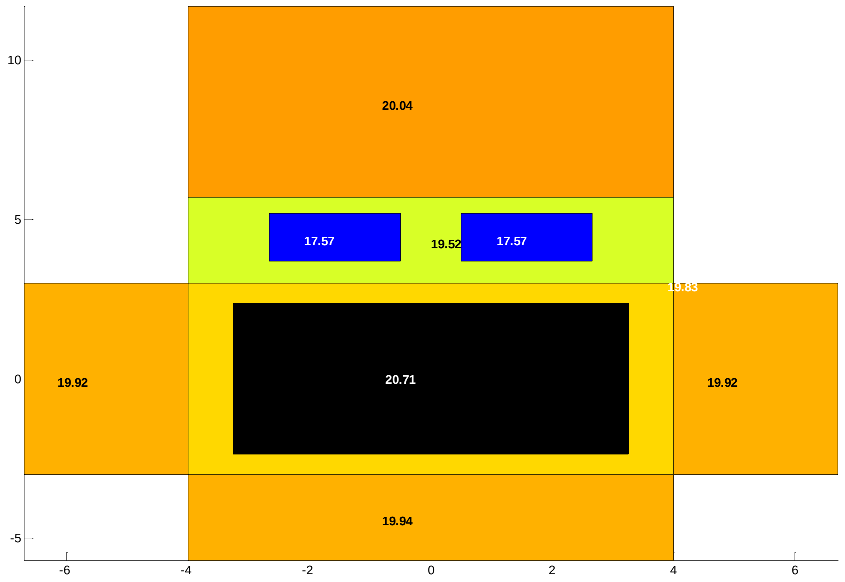


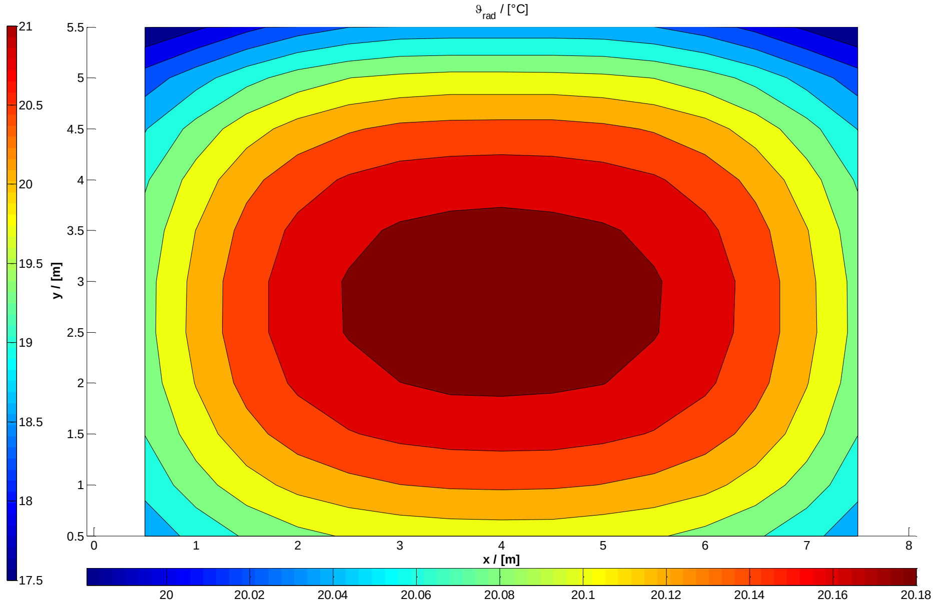


STEADY STATE: floor large W30 centered

Operative Temperature = 20°C
Qdot_tot = 205.46 W
Temperature Heater = 20.71 °C
Radiative exchange Heater = 68.99 %

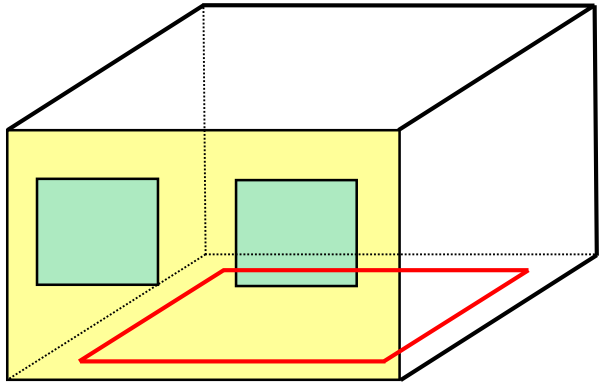


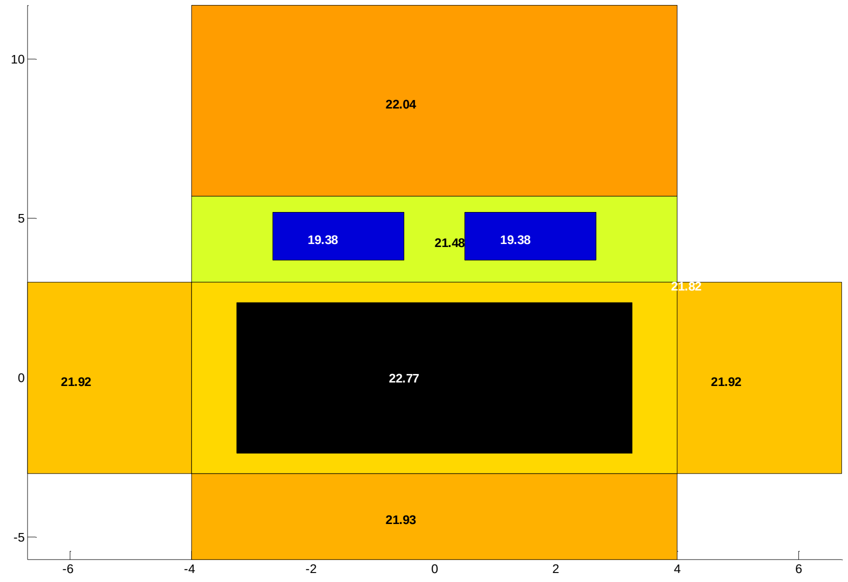


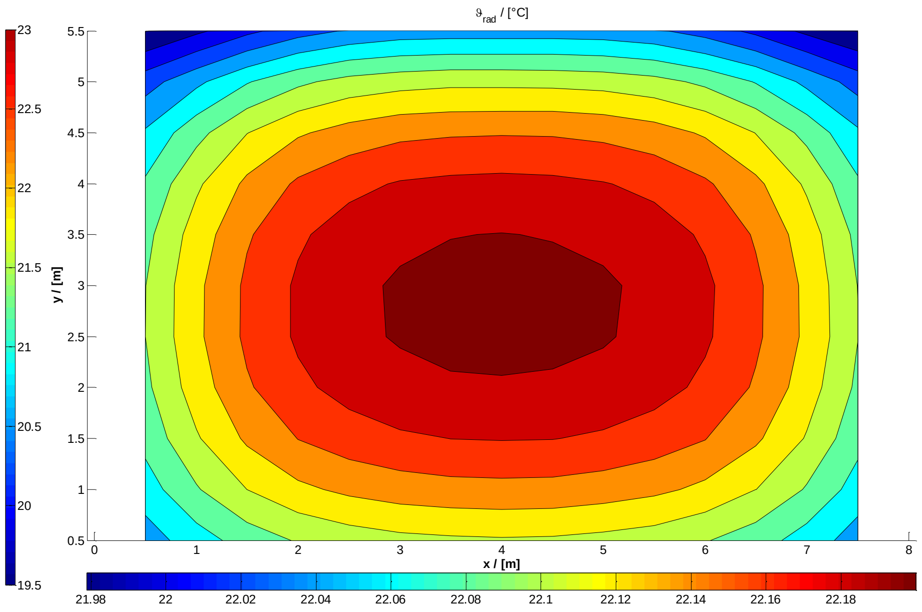


STEADY STATE: floor large W30 centered

Operative Temperature = 22°C
Qdot_tot = 226.34 W
Temperature Heater = 22.77 °C
Radiative exchange Heater = 68.95 %

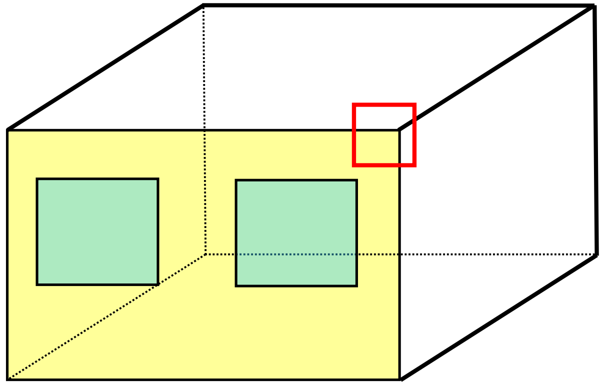


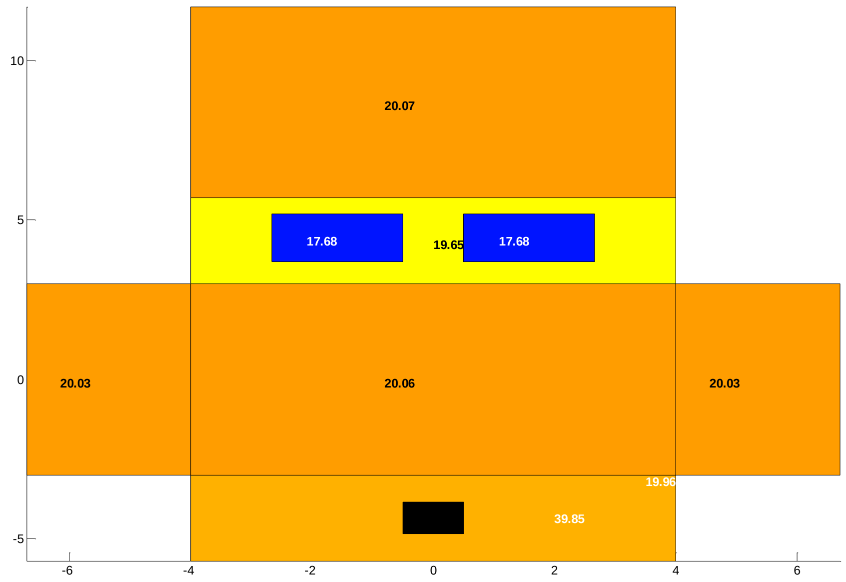


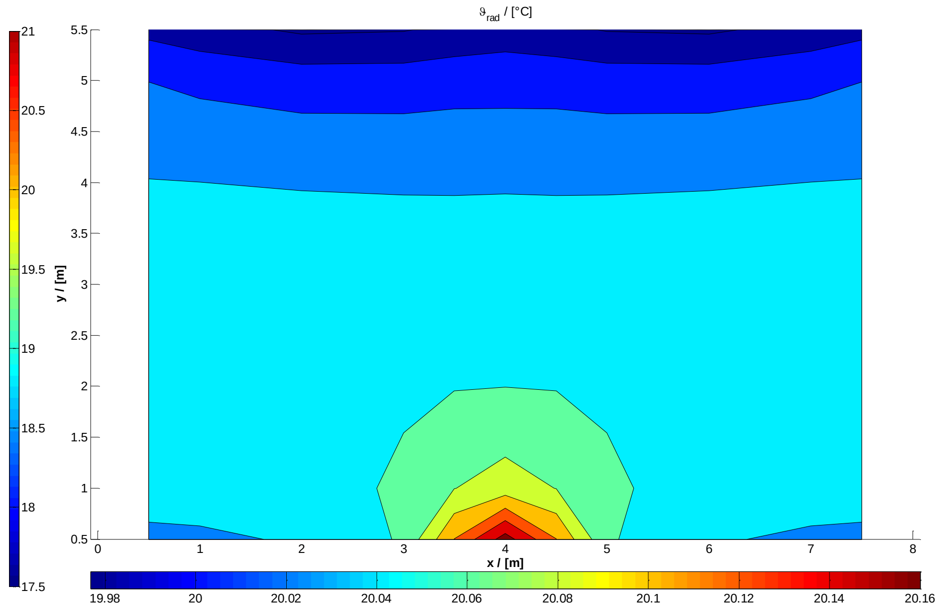


STEADY STATE: rear wall small W30 centered

Operative Temperature = 20°C
Qdot_tot = 207.06 W
Temperature Heater = 39.85 °C
Radiative exchange Heater = 57.77 %

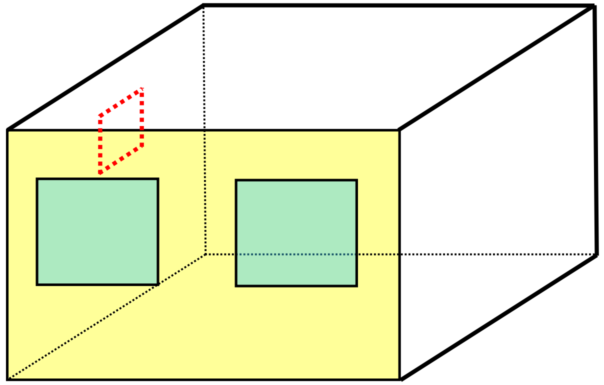


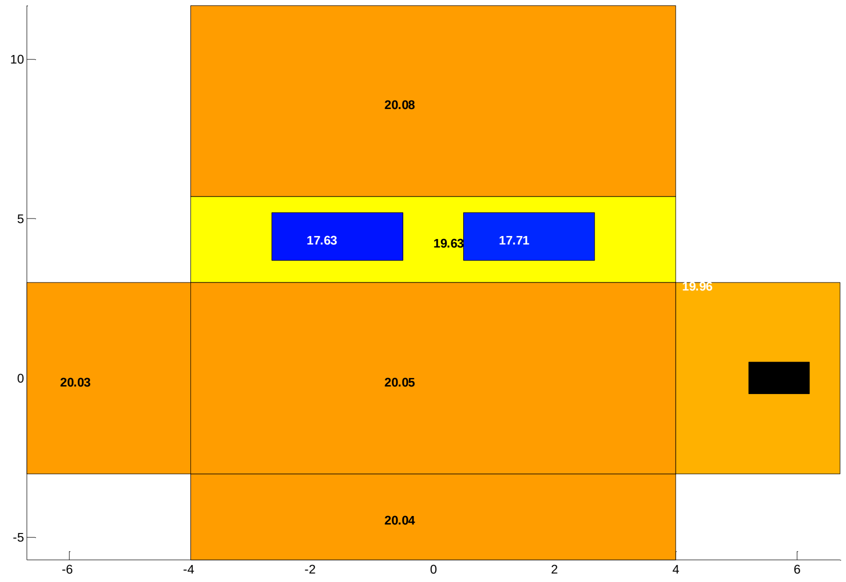


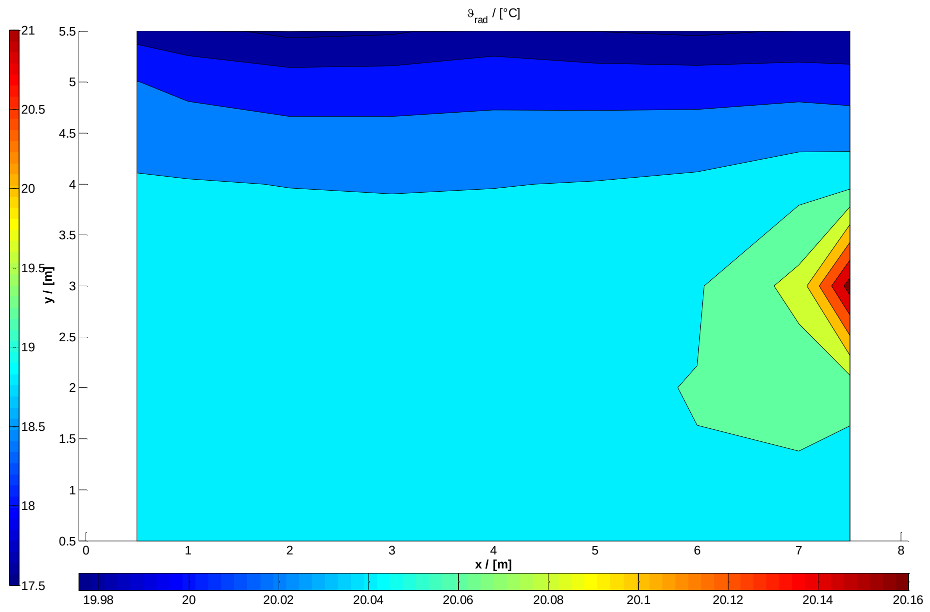


STEADY STATE: sidewall small W30 centered

Operative Temperature = 20°C
Qdot_tot = 206.97 W
Temperature Heater = 39.85 °C
Radiative exchange Heater = 57.70 %







STEADY STATE: sidewall large W30 centered

Operative Temperature = 20°C
Qdot_tot = 206.77 W
Temperature Heater = 22.53 °C
Radiative exchange Heater = 70..61 %