

EXPERIMENTAL VALIDATION OF THE PROGRAM VOLTRA FOR 3D TRANSIENT HEAT TRANSFER



physibel

Introduction

Two experimental validations of the program VOLTRA for simulating 3D transient heat transfer were done on a small glazed wooden box.

In the first **indoors** experiment the transient heat transfer due to a sudden internal power source was investigated.

In the second experiment the box was put **outdoors**, allowing **validating the solar processor** module in **VOLTRA**.

The experimental validations were done in the framework of the SBO project IWT 050154 research program “Heat, air and moisture performance engineering. A whole building approach.”

Box description



removable roof

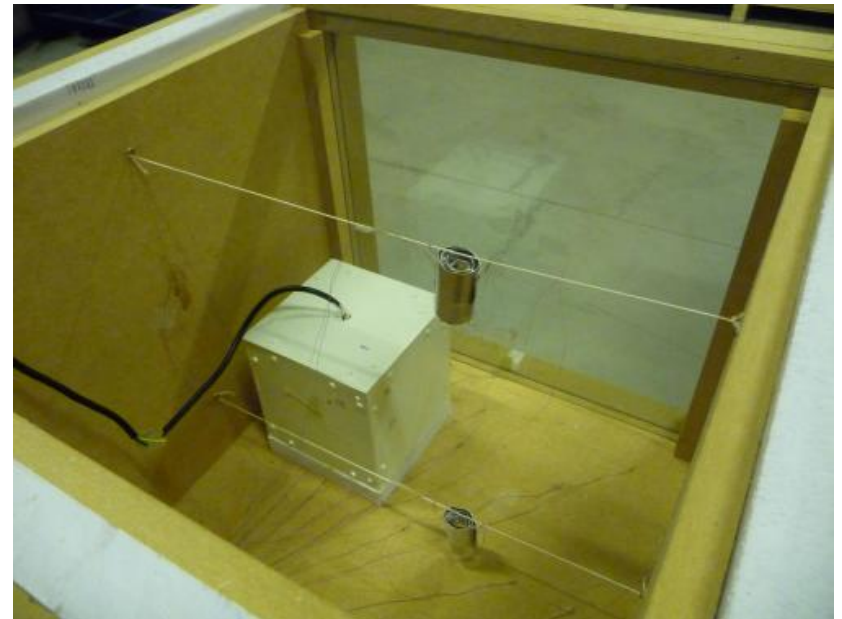
box double glazing (MDF spacer)

box wall (materials: MDF, XPS)

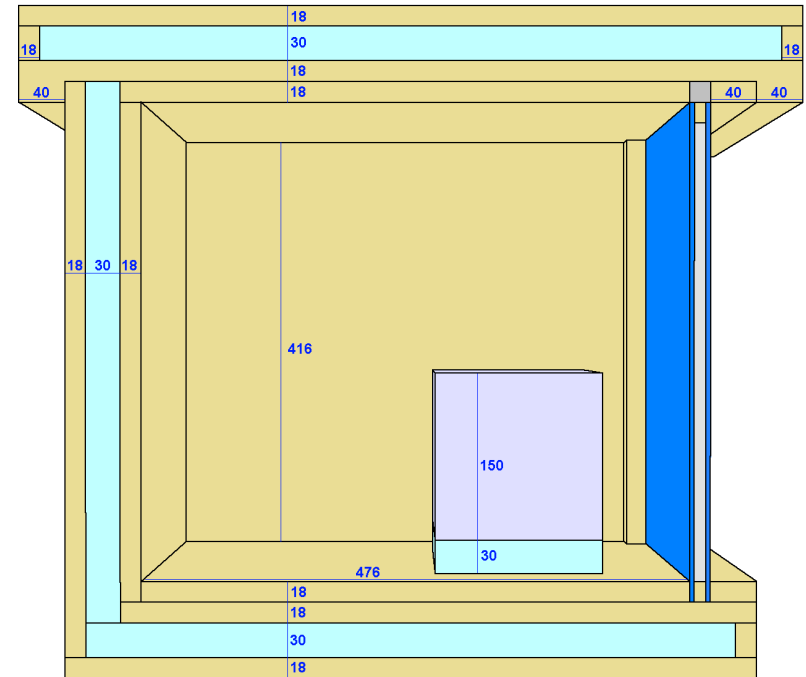
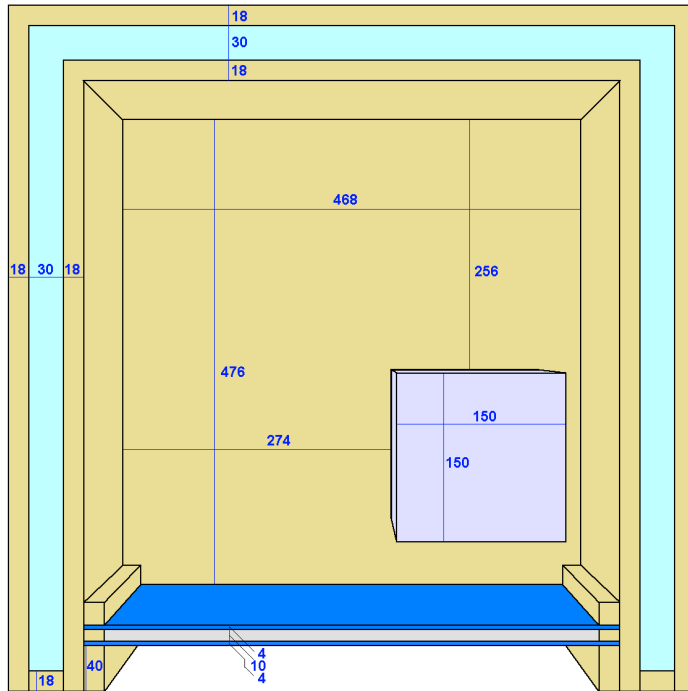
copper box (containing a 60 W lamp)

copper plate

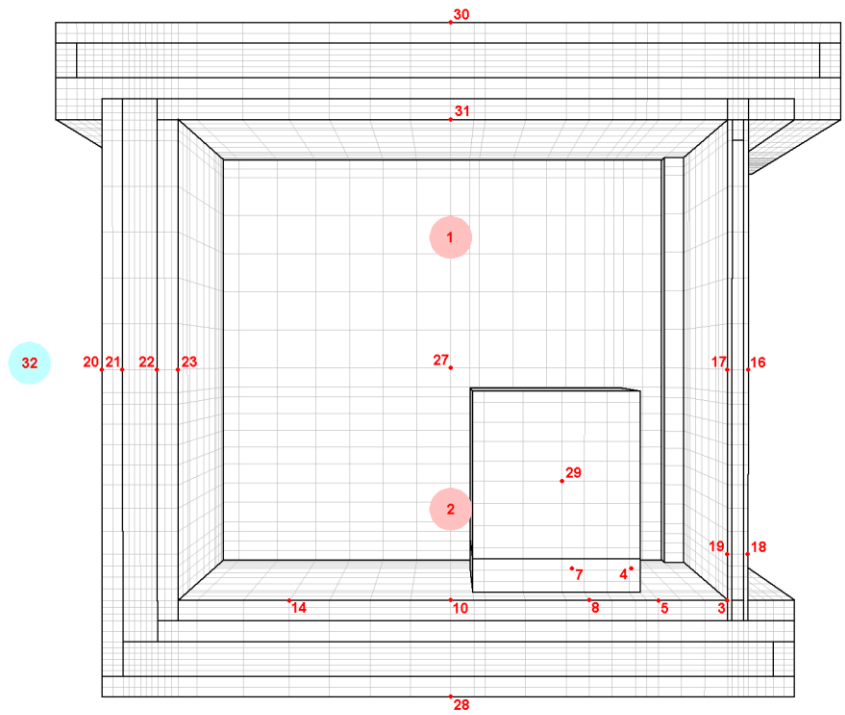
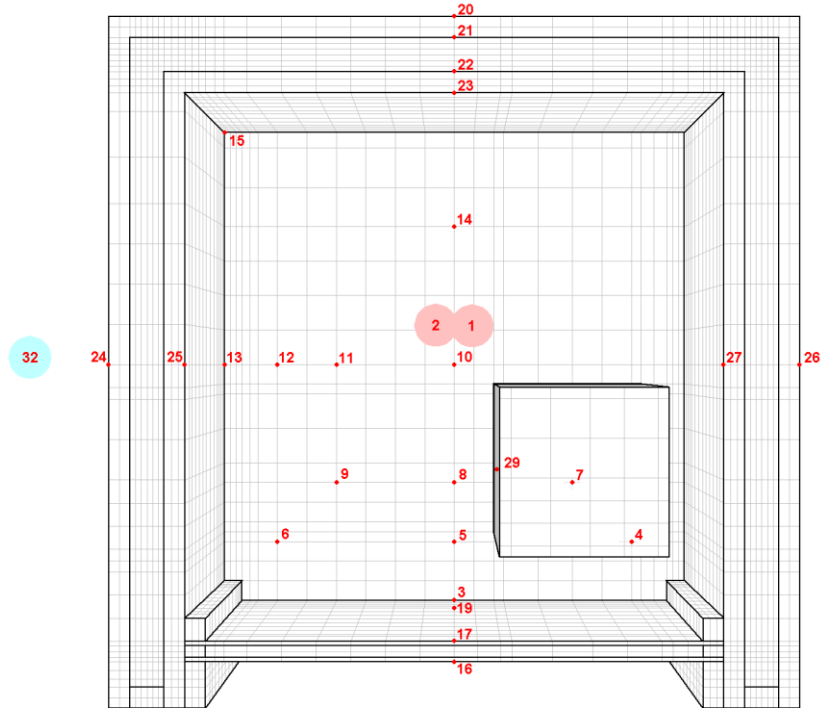
datalogger space



Box description

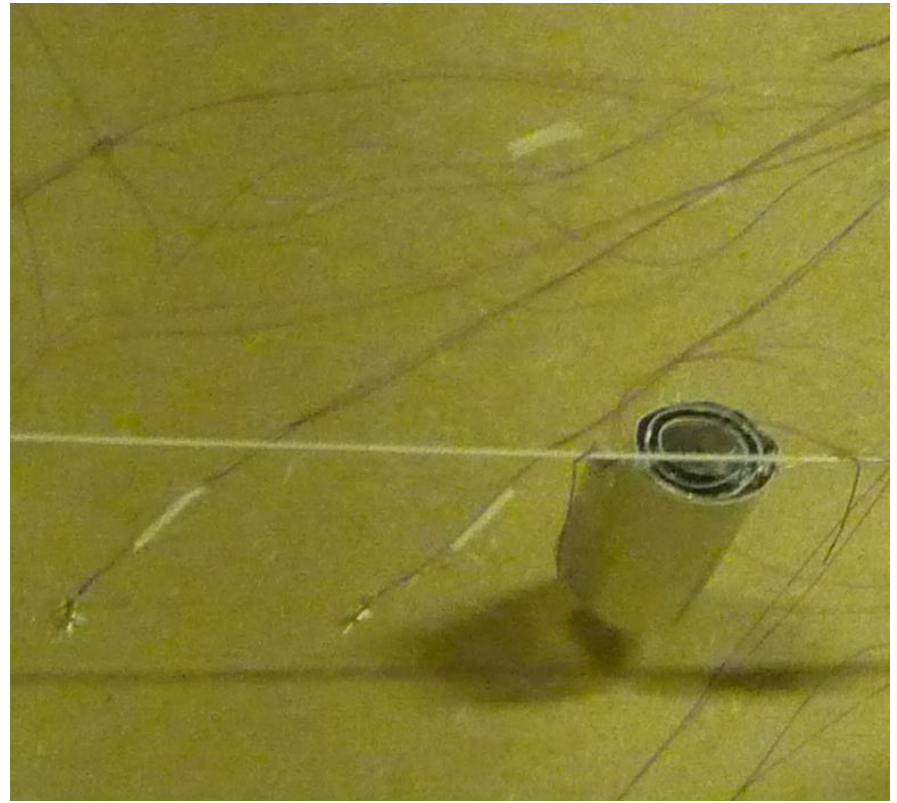
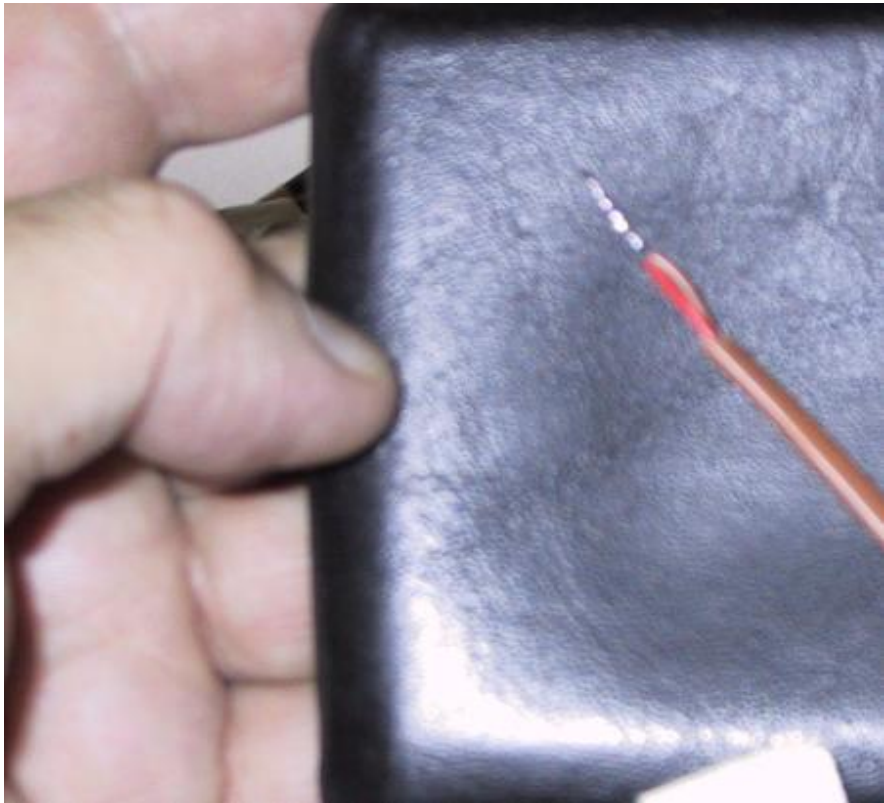


Box description



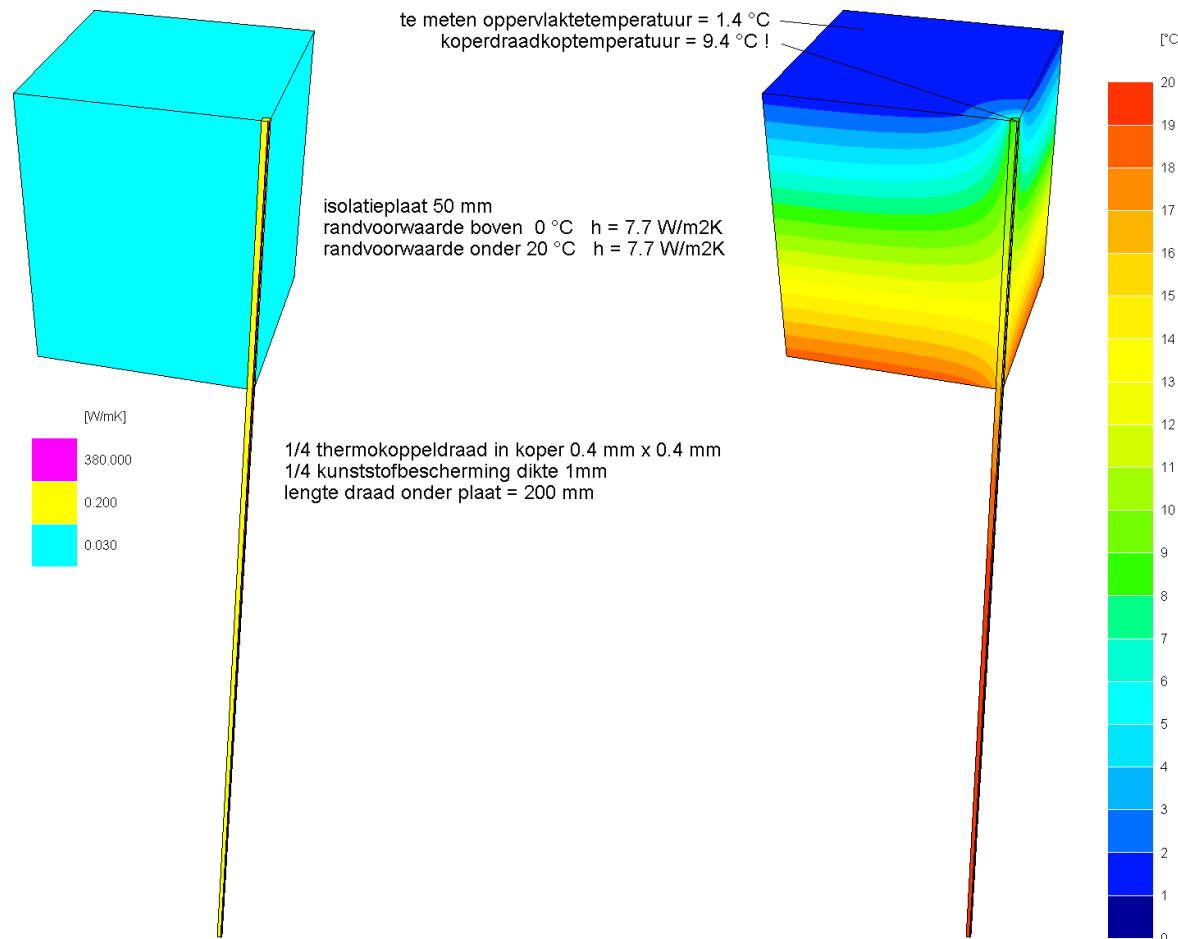
Box description

Importance of the thickness of the thermocouples (copper-constantan) : 0.4 mm (as almost installed) is too thick !



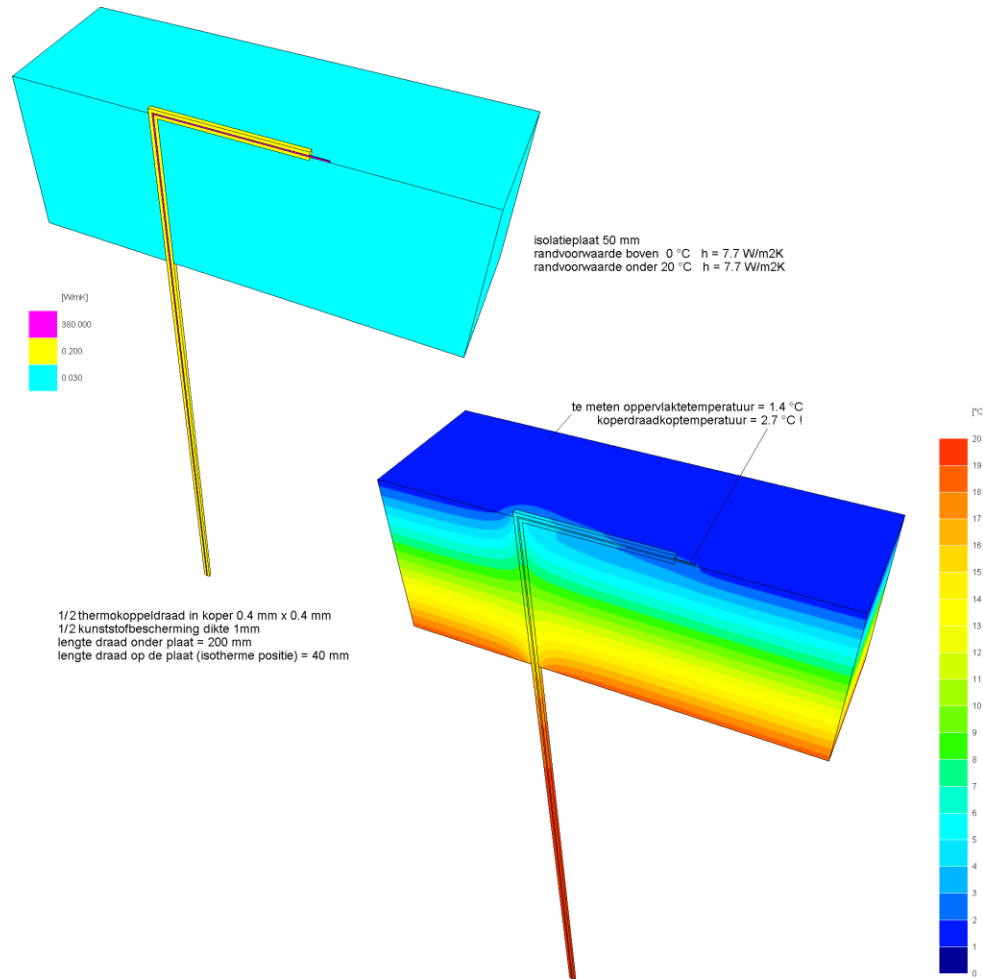
Box description

Importance of the thickness of the thermocouples
(copper-constantan) : 0.4 mm (as almost installed) is too
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Box description

Importance of the thickness of the thermocouples (copper-constantan) : 0.4 mm (as almost installed) is too thick !

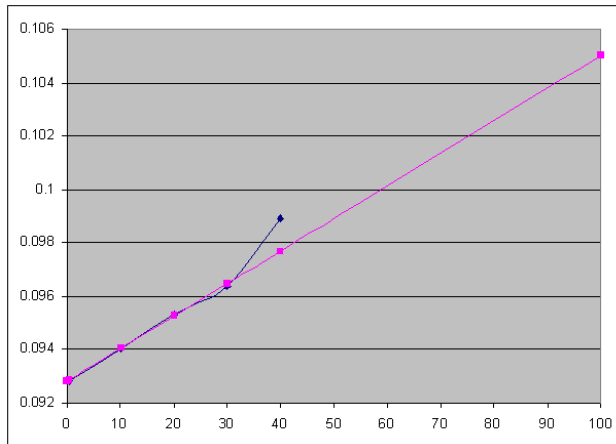


Material properties

Thermal conductivity λ [W/mK]: measured / literature

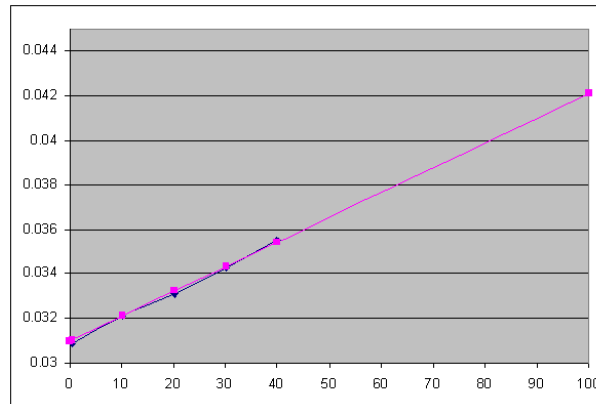
MDF ($\rho = 648 \text{ kg/m}^3$)

measurement reference	temperature °C	λ measured W/mK	λ assumed W/mK
	0.00		0.0928
505	0.36	0.0928	0.0928
515	10.23	0.0940	0.0940
1525	20.14	0.0953	0.0953
2535	30.07	0.0964	0.0965
3545	39.95	0.0989	0.0977
	100.00		0.1050



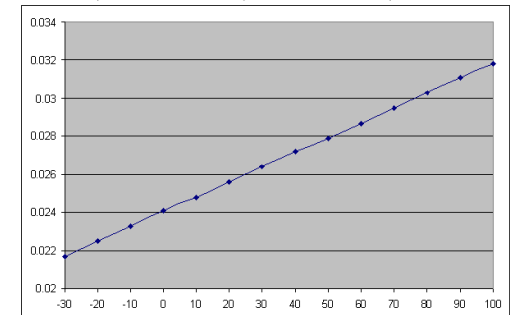
XPS ($\rho = 34.9 \text{ kg/m}^3$)

measurement reference	temperature °C	λ measured W/mK	λ assumed W/mK
	0		0.031
505	0.36	0.0309	0.0310
515	10.23	0.0321	0.0321
1525	20.08	0.0331	0.0332
2535	30.09	0.0343	0.0343
3545	39.98	0.0355	0.0354
	100.00		0.0421



air ($\rho = 1.2 \text{ kg/m}^3$)
 $c = 1005 \text{ J/kgK}$

temperature °C	λ W/mK
-30	0.0217
-20	0.0225
-10	0.0233
0	0.0241
10	0.0248
20	0.0256
30	0.0264
40	0.0272
50	0.0279
60	0.0287
70	0.0295
80	0.0303



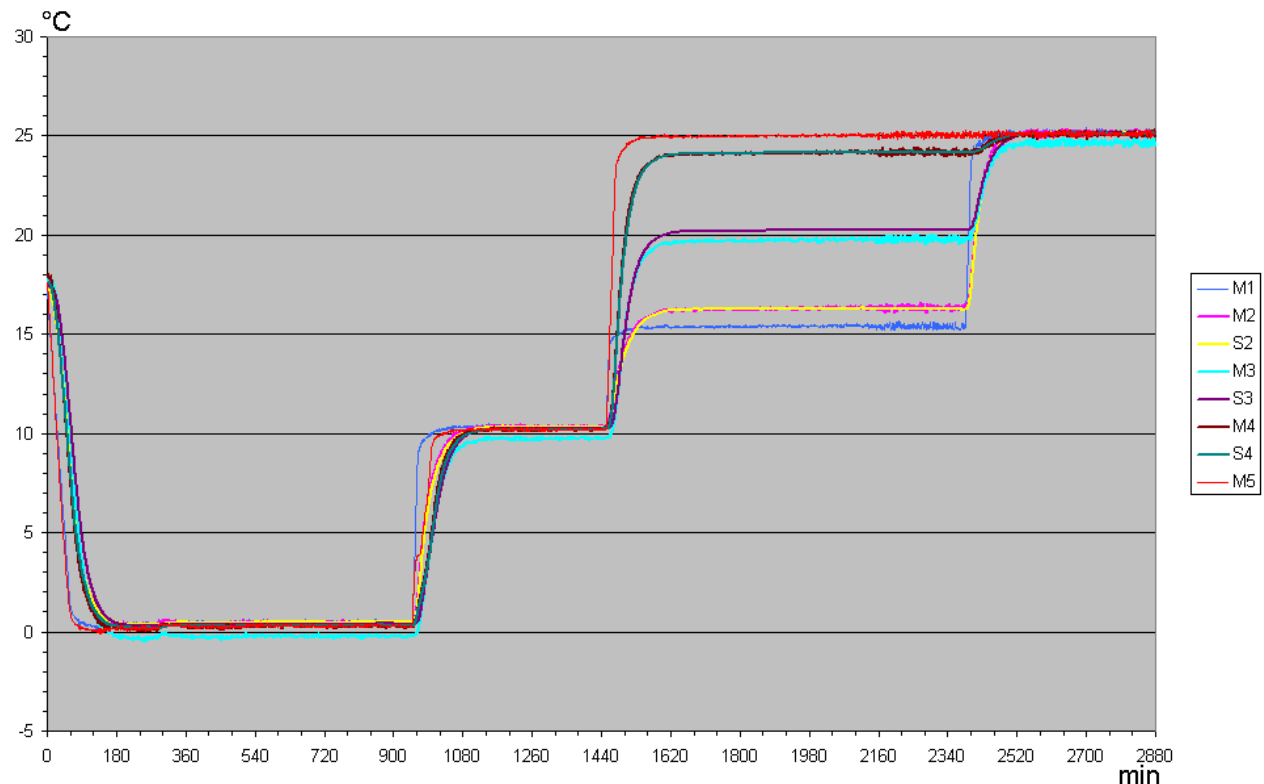
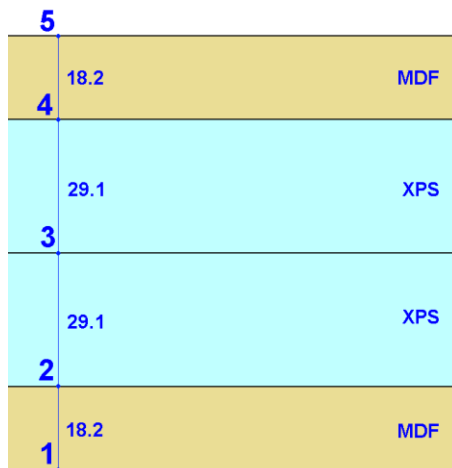
soda lime (density $\rho = 2500 \text{ kg/m}^3$): $\lambda = 1.0 \text{ W/mK}$, $c = 650 \text{ J/kgK}$

copper (density $\rho = 8900 \text{ kg/m}^3$): $\lambda = 380 \text{ W/mK}$, $c = 380 \text{ J/kgK}$

Material properties

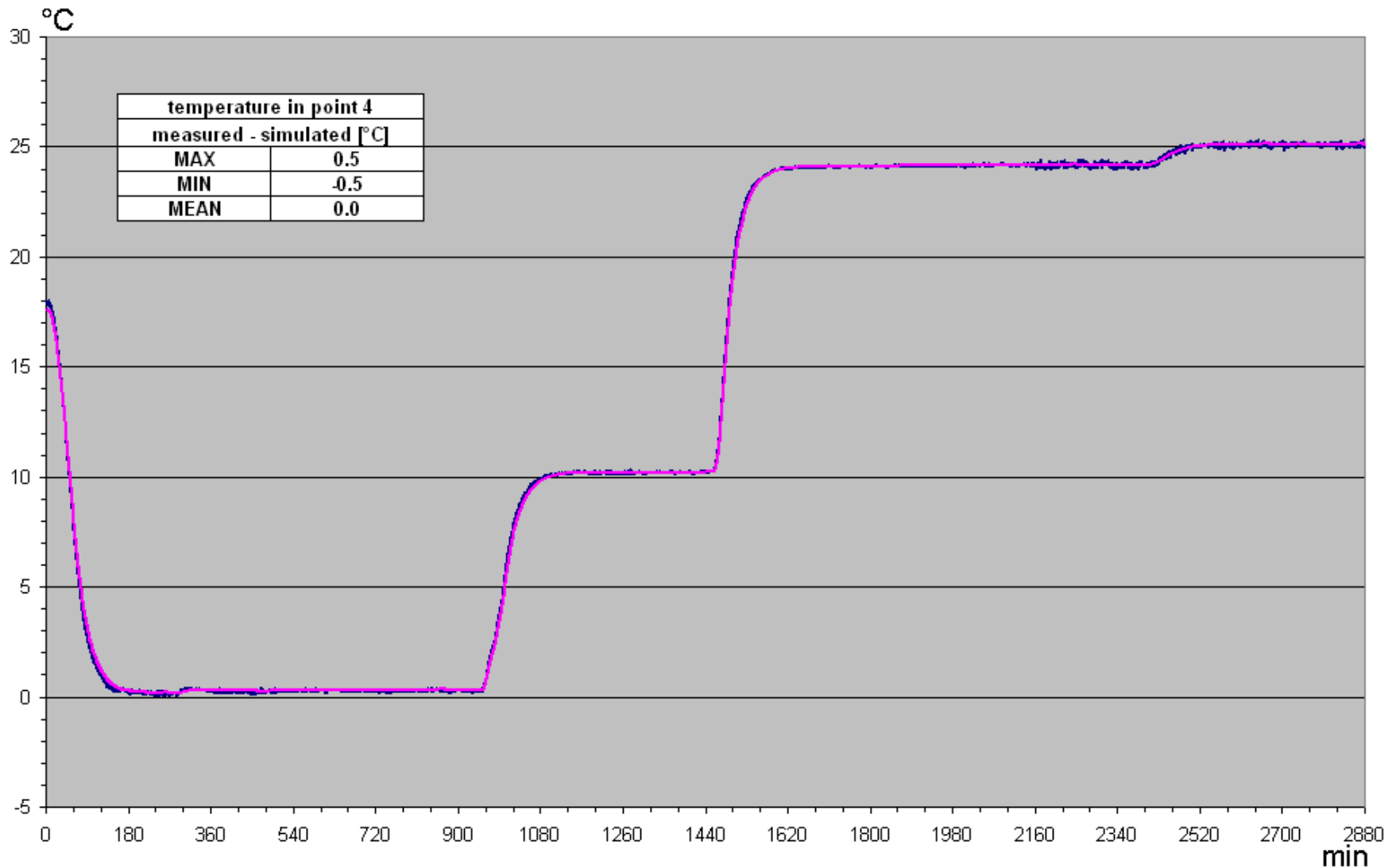
Specific heat c [J/kgK]: measurement / literature

In the guarded hot plate apparatus hot plate used for the measurement of the thermal conductivity of MDF and XPS specified above, a sandwich of MDF and XPS (Figure 10) was exposed to variable temperatures at both sides (points 1 and 5) during 2 days (2880 minutes). The 1D transient heat transfer was simulated using the program VOLTRA with $c = 1470 \text{ J/kgK}$ for XPS and $c = 1450 \text{ J/kgK}$ for MDF. The values for the specific heat of wood based panels found in literature vary in a quite **wide range: 1200 – 2000 J/kgK**. The value **$c = 1450 \text{ J/kgK}$** resulted in the best fit from the results of multiple simulations.



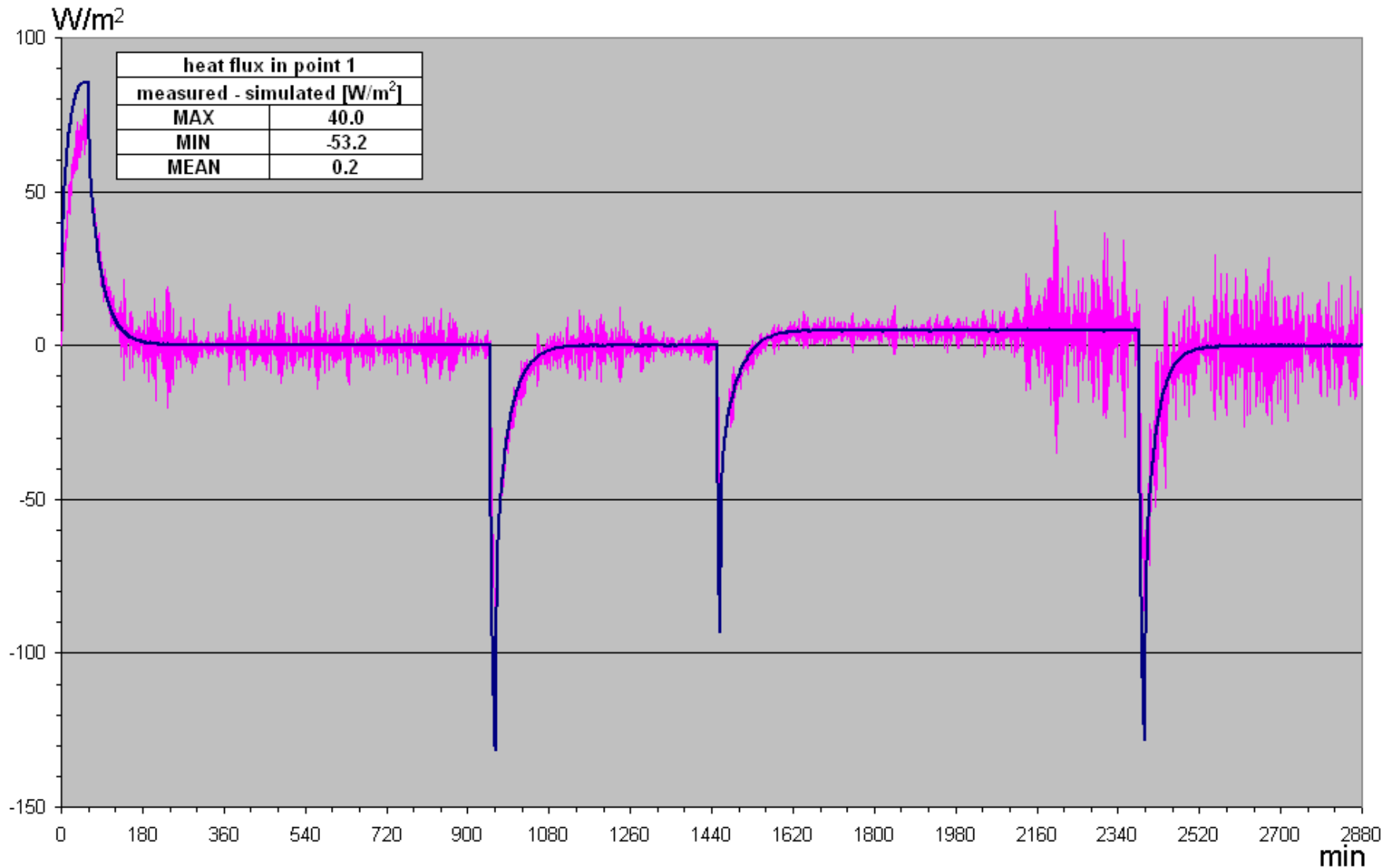
Material properties

Temperature course in point 4: measurement vs.



Material properties

Heat flux in point 4: measurement vs. simulation



Surface properties

Long wave emissivity

soda lime glazing: $\varepsilon = 0.9$

other material surfaces: $\varepsilon = 0.95$

Solar properties

MDF surfaces: $\alpha_s = 0.65$

soda lime:

Glazing layer definition		standard reference glazing ASHRAE 4 mm						
Solar transmission factor	$\tau_s =$	0.860						
Solar reflection factor	$\rho_s =$	0.080						
Solar absorption factor	$\alpha_s =$	0.060						
Solar transmission factor after deduction of reflection	$\tau_{sVOLTRA} =$	0.935						
Solar reflection factor	$\rho_{sVOLTRA} =$	0.080						
Solar absorption factor after deduction of reflection	$\alpha_{sVOLTRA} =$	0.065						
Angle of incidence [°]	$\gamma =$	0	15	30	45	60	75	90
Reflection percentage	$\rho =$	0.00	0.00	0.00	0.02	0.08	0.33	1.00
Reflection factor as a function of angle of incidence	$\rho_{sVOLTRA} =$	0.080	0.080	0.080	0.098	0.154	0.384	1.000

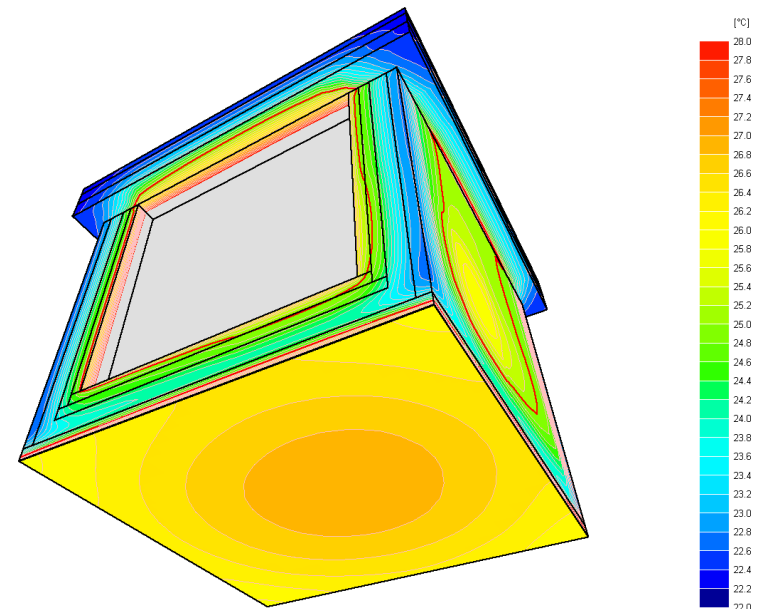
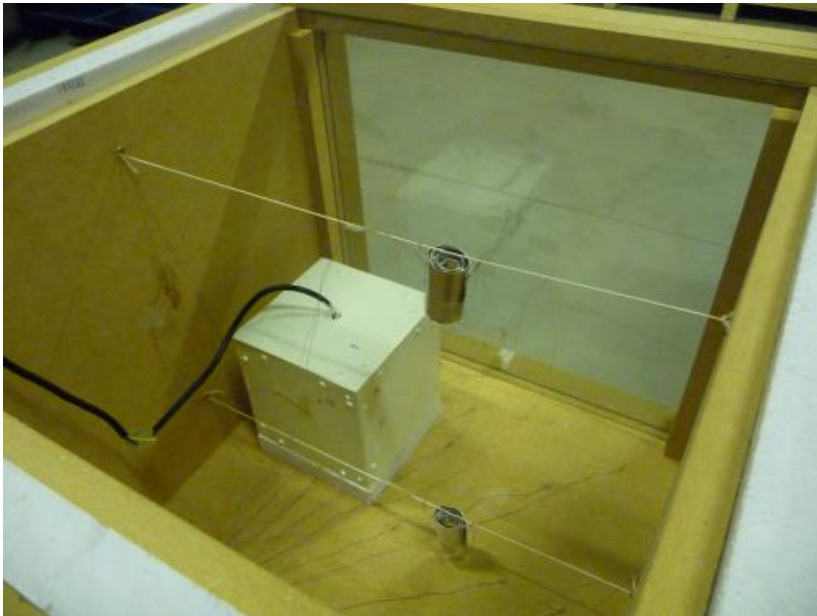
Internal power experiment

3 boundary conditions fully determine the heat transfer in the box

The **laboratory temperature**. The air temperature and the mean wall surface temperatures are assumed to be the same.

The **copper plate temperature** assumed as homogeneous.
The numerically predicted temperature gradient is only 1 °C.

The **power of the bulb** used: 0 W for $t = 0$, and 56 W for $t > 0$.



Internal power experiment

VOLTRA simulation data.

Laboratory side: BC_SKY Physibel boundary condition type

The radiation between the box surface elements and the laboratory is simulated using non-linear view factor based radiation.

The convection between the box surface elements and the air is calculated

empirically

$$q_c = h_c (\theta_{\text{air}} - \theta_{\text{surface}}) \quad h_c = 1.46 (\theta_{\text{air}} - \theta_{\text{surface}})^{1/3}$$

A uniform convective heat transfer coefficient h_c is taken into account at each moment.

Box side: BC_FREE Physibel boundary type

The radiation between the box surface elements is simulated using non-linear view factor

based radiation.

The unknown air temperature is assumed to be homogeneous.

The convection between the box surface elements and the air is calculated

empirically:

cf. above.

Internal power experiment

VOLTRA transient simulation results.

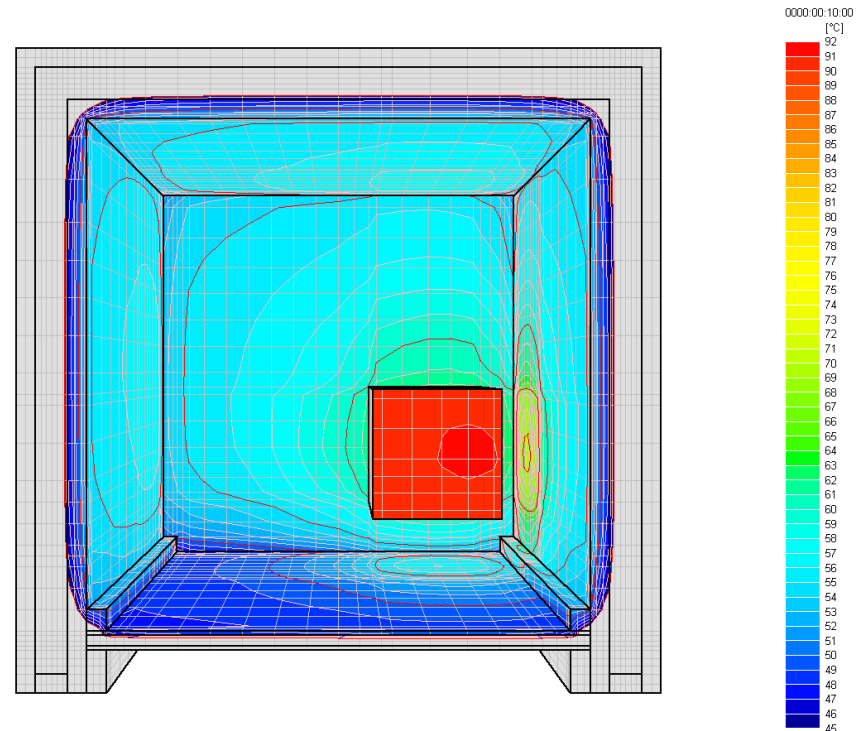
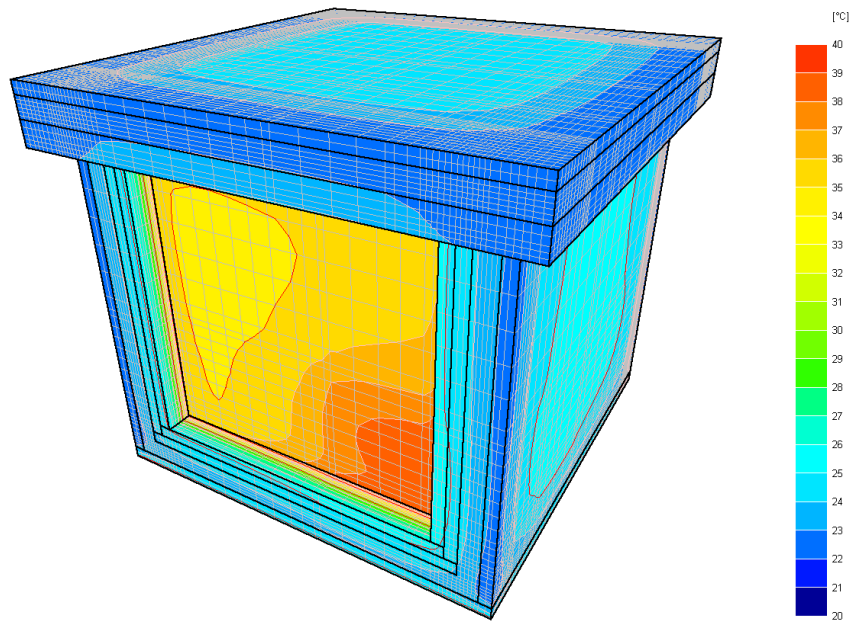
[Box Internal Power Exp External View.avi](#)

[Box Internal Power Exp Internal View.avi](#)

[Box Internal Power Exp isotherms 15steps.ppt](#)

[box internal power charts.ppt](#)

VOLTRA steady state simulation results.



Internal power experiment

VOLTRA steady state simulation results.

	thermocouple	measured mean temperature [°C]	standard deviation [°C]	simulated temperature [°C]	measured - simulated [°C]
air temperature indoors high	01	60.8	0.3	58.6	-2.2
air temperature indoors low	02	54.9	0.3	58.6	3.7
floor internal surface A	03	46.4	0.3	50.4	4.0
floor internal surface B	04	56.1	0.4	59.7	3.6
floor internal surface C	05	54.3	0.4	56.8	2.5
floor internal surface D	06	50.7	0.3	53.7	3.0
floor internal surface E	07	66.4	0.5	65.8	-0.6
floor internal surface F	08	57.2	0.4	59.5	2.3
floor internal surface G	09	52.5	0.3	56.1	3.6
floor internal surface H	10	56.1	0.3	58.0	1.9
floor internal surface I	11	53.4	0.3	56.1	2.7
floor internal surface J	12	52.5	0.3	55.5	3.0
floor internal surface K	13	50.4	0.3	53.7	3.3
floor internal surface L	14	54.1	0.3	56.3	2.2
floor internal surface M	15	-	-	50.6	-
glazing external surface middle	16	35.2	0.3	35.3	0.1
glazing internal surface middle	17	50.8	0.3	50.3	-0.5
glazing external surface lower	18	33.2	0.2	36.3	3.1
glazing internal surface lower	19	50.7	0.3	51.7	1.0
wall north external surface middle	20	24.8	0.2	25.0	0.2
wall north interface external board / insulation middle	21	29.7	0.2	29.9	0.2
wall north interface insulation / internal board middle	22	51.7	0.3	51.6	-0.1
wall north surface internal middle	23	56.5	0.3	56.2	-0.3
wall west external surface middle	24	24.8	0.2	25.0	0.2
wall west internal surface middle	25	56.4	0.3	56.2	-0.2
wall east external surface middle	26	24.9	0.2	25.2	0.3
wall east internal surface middle	27	58.2	0.3	58.3	0.1
copper plate middle	28	25.6	0.3	25.6	-
isothermal heater	29	93.1	0.6	91.5	-1.6
roof external surface middle	30	24.4	0.2	24.7	0.3
roof internal surface middle	31	57.5	0.3	56.7	-0.8
air temperature outdoors	32	22.3	0.2	22.3	-

Discussion.

The air temperatures measured at 2 levels (4 cm and 34 cm above the floor plate) show a considerable air temperature gradient (5.9 °C over 30 cm in steady state) due to the buoyancy. The simulation with VOLTRA, using the BC_FREE type for the box indoor environment, assumes a uniform air temperature. The simulated air temperature value lies in between these two measured temperature. Due to the air temperature gradient, the simulated temperatures at the floor level (3 up to 15) overestimate the measured ones, and the simulated temperature at the roof level (30) underestimates the measured one. The overestimation at the floor level is more important than the underestimation at the roof level. At the central level (positions 16, 17, 20, 21, 22, 23, 24, 25, 26, 27) the correspondence between simulated and measured temperatures is very good (≤ 0.5 °C).

It can be expected that the air temperature gradient in the outdoors test will be much weaker. Indeed the solar radiation will strike mainly the floor, and due to the heating up of the box by this 'floor heating' a weak temperature gradient can be expected. The correspondence between the measured and simulated temperatures in the transient period (0h – 12h) is excellent.

Outdoors experiment

In Heverlee, from 24 until 28 September 2008.

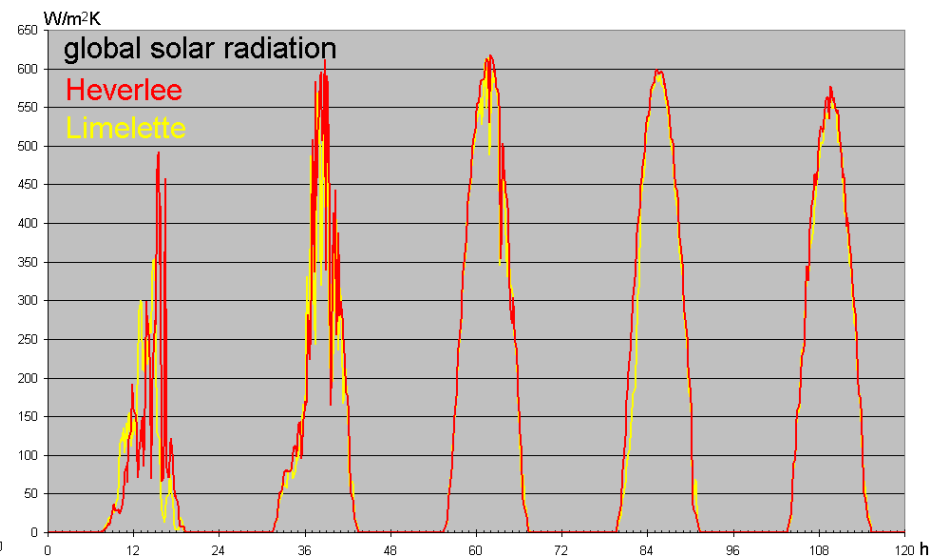
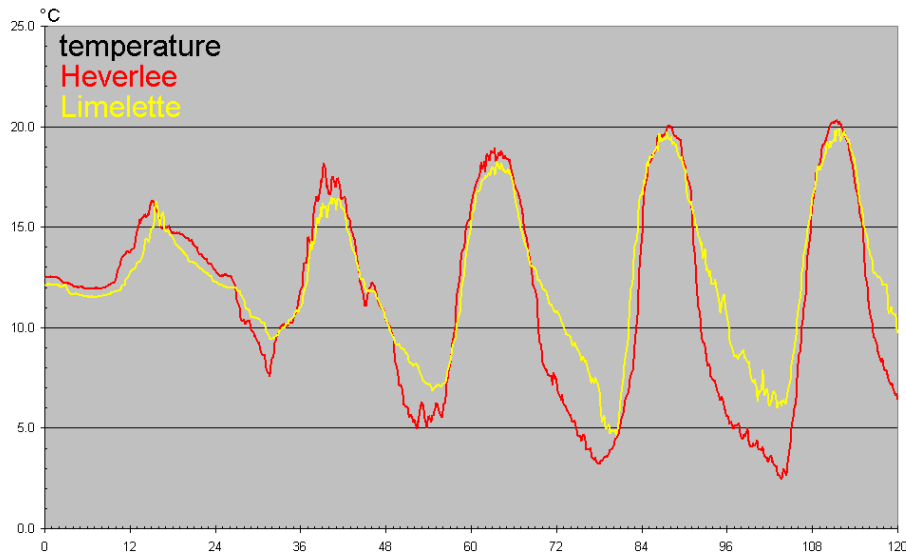
The box is oriented to the South East (39.5° from South).

Some buildings and trees in the environment obstruct the diffuse solar radiation. In the simulation they were entered as a horizon of 7° high in all directions, with a supplement up to 13° from -65° (South-East-East) to $+25^\circ$ (South-South-West).



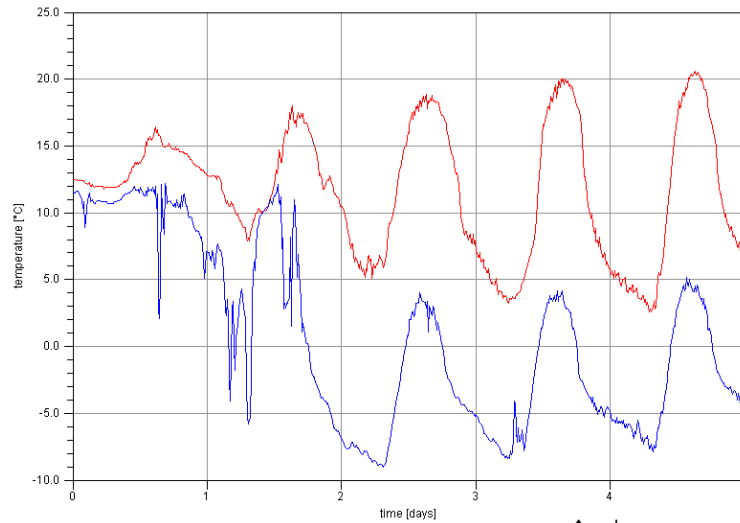
Outdoors experiment

The climate station in Heverlee doesn't record the horizontal diffuse solar radiation, neither the infrared sky radiation. Therefore these data were taken from the climate station in Limelette (about 20 km south of Heverlee). This method is justified by the agreement between the air temperature courses and the horizontal global solar radiation courses at both sites.

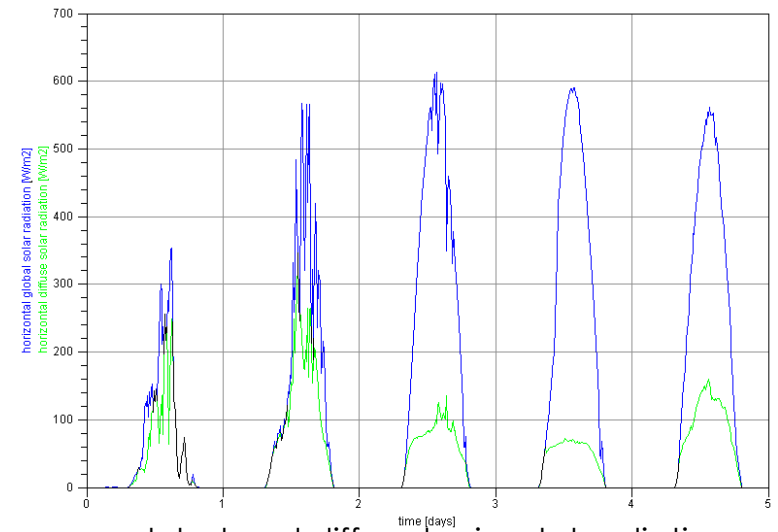


Outdoors experiment

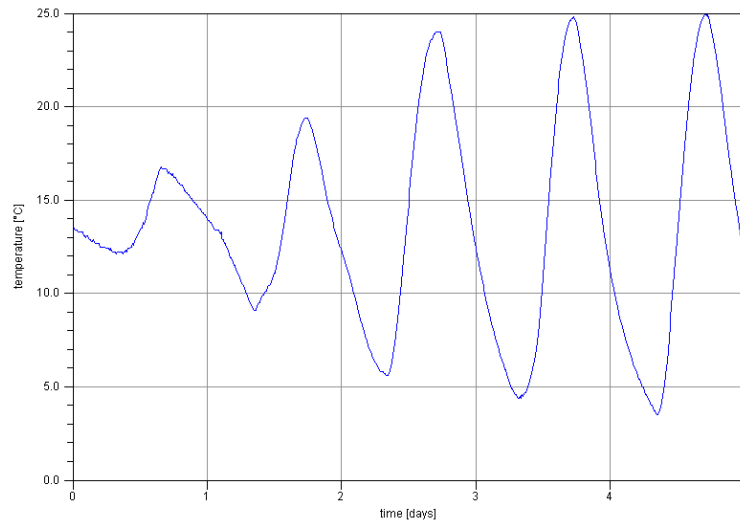
Simulation boundary conditions



air temperature and sky temperature ↑ ↓ copper plate temperature



global and diffuse horizontal radiation



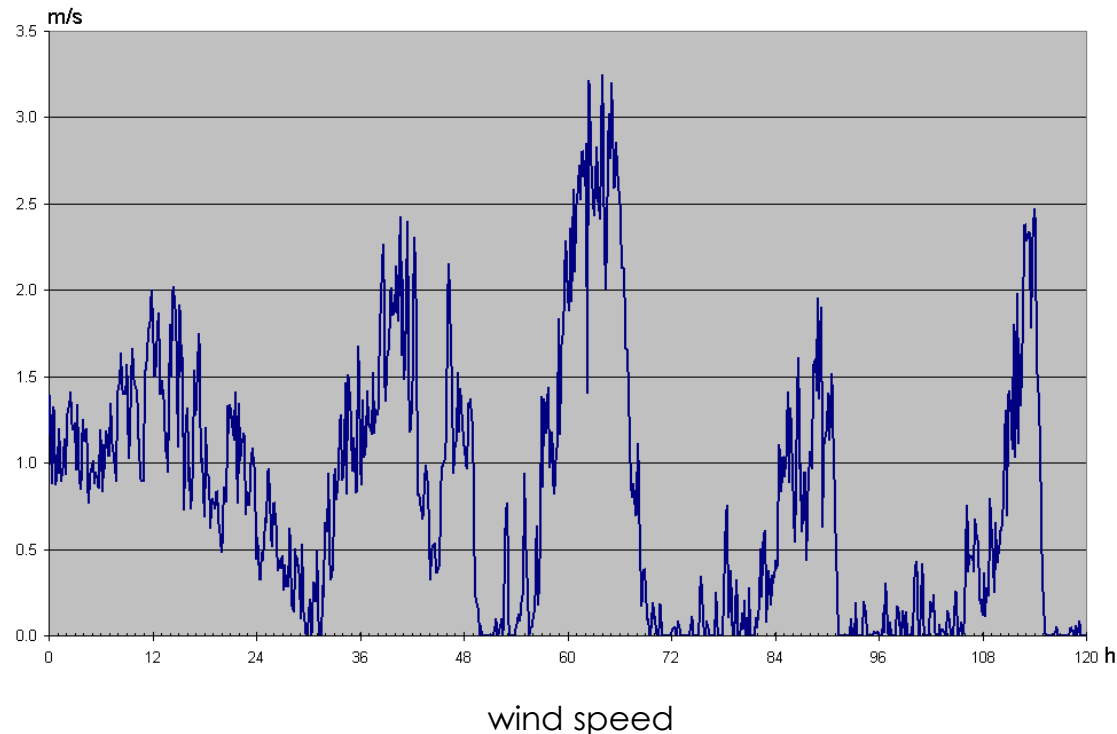
Outdoors experiment

Simulation boundary conditions

The radiation between the box roof surface and the outdoors is simulated (non-linear view factor based radiation) using the sky temperature. For the box walls the average of the sky temperature and the air temperature is used, taking into account that the walls look for 50 % to the sky and for 50% to the ground assumed having the air temperature.

The convection between the box surface elements is calculated empirically: with $h_c = 8 \text{ W/m}^2\text{K}$. This value is representative for a wind speed of 1 m/s.

$$q_c = h_c(\theta_{air} - \theta_{surface})$$



Outdoors experiment

VOLTRA simulation data.

Outdoors: BC_SKY Physibel boundary condition type
See previous slide

Box side: BC_FREE Physibel boundary type
The radiation between the box surface elements is simulated using non-linear view factor based radiation.
The unknown air temperature is assumed to be homogeneous.
The convection between the box surface elements and the air is calculated empirically:

$$q_c = h_c (\theta_{\text{air}} - \theta_{\text{surface}})$$

$$h_c = 1.72 (\theta_{\text{air}} - \theta_{\text{surface}})^{1/4}$$

Outdoors experiment

VOLTRA transient simulation results.

[box outdoors 5days external view.avi](#)

[box outdoors 5days internal view.avi](#)

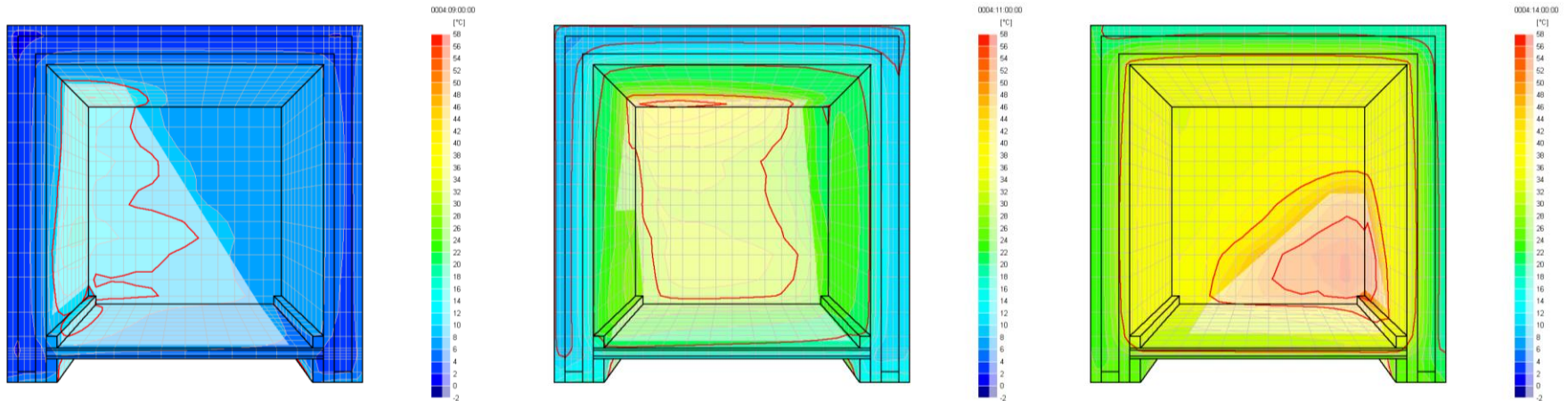
[box outdoors 28 sept external view.avi](#)

[box outdoors 28 sept internal view.avi](#)

[box outdoors 28 sept front view.avi](#)

[box outdoors 28 sept.ppt](#)

[box outdoors charts.ppt](#)



Outdoors experiment

	data Box_Outdoors_Exp.vtr				data Box_Outdoors_Exp_double_grid.vtr		
	point	measured - simulated			point	measured - simulated	
		min [°C]	max[°C]			min [°C]	max[°C]
air temperature indoors high	1	0.9	5.3		1	0.8	4.8
air temperature indoors low	2				2		
floor internal surface A	3	0.3	6.1		3	0.1	5.7
floor internal surface B	4	-2.9	2.5		4	-1.7	1.9
floor internal surface C	5	-1.7	3.2		5	-1.7	1.9
floor internal surface D	6	-0.5	5.4		6	-0.6	2.6
floor internal surface E	7	-3.8	2.2		7	-2.7	1.8
floor internal surface F	8	-4.5	3.0		8	-3.3	1.8
floor internal surface G	9	-2.1	2.9		9	-2.1	1.8
floor internal surface H	10	-2.2	3.0		10	-1.9	1.8
floor internal surface I	11	0.1	3.2		11	-1.8	1.9
floor internal surface J	12	-0.8	4.0		12	-1.0	2.2
floor internal surface K	13	-1.6	2.7		13	-1.3	2.1
floor internal surface L	14				14		
floor internal surface M	15	-2.5	2.0		15	-2.7	1.9
glazing external surface middle	16	1.3	5.8		16	1.3	5.8
glazing internal surface middle	17	1.0	5.3		17	1.0	5.1
glazing external surface lower	18				18		
glazing internal surface lower	19	1.1	4.3		19	1.0	4.9
wall north external surface middle	20	-0.8	3.2		20	-0.8	3.2
wall north interface external board / insulation middle	21	-0.2	2.9		21	-0.2	2.9
wall north interface insulation / internal board middle	22	0.8	4.0		22	0.7	3.9
wall north surface internal middle	23	0.7	4.1		23	0.6	4.0
wall west external surface middle	24				24		
wall west internal surface middle	25	-0.8	3.8		25	-1.9	2.9
wall east external surface middle	26	-1.9	3.7		26	-2.0	3.6
wall east internal surface middle	27	0.7	2.9		27	0.6	2.3
copper plate middle	28	0.0	0.0		28	0.0	0.0
isothermal heater	29				29		
roof external surface middle	30	-10.1	-1.6		30	-10.1	-1.6
roof internal surface middle	31	0.4	2.8		31	0.2	2.3
air temperature outdoors	32				32		
	mean	-1.1	3.3		mean	-1.1	2.8

Outdoors experiment

Discussion

The supposition of a weaker air temperature gradient compared to the one in the internal power experiment couldn't be confirmed directly because of a failure of the thermocouple in position 2 (lower air temperature). The fact that the measured temperatures on the central floor (P10), on the central ceiling (P31) and in the higher air position (P2) are very close to each other (a difference of about 1 °C only occurs, except during a short noon period) confirms indirectly a weak air temperature gradient. The fact that the differences between measured and simulated temperatures all similar for all positions (and not higher for the floor positions as in the internal power experiment) is another indication of a weak air temperature gradient.

Generally spoken the correspondence between the measured and simulated temperature courses is good. The highest differences occur in the early afternoon during the 3 last sunny days, which is normal because at that moment the highest temperature gradient (about 40 °C) occurs over the box.

The simulated air temperature is maximally 4.8 °C lower than the measured one. A possible explanation is the uniform convective heat transfer coefficient assumed in the simulation. At each moment a uniform coefficient $h_c = 1.72 \Delta\theta^{1/3}$ is used with $\Delta\theta$ being the maximum temperature difference between any surface element and the air occurring at that moment. The value is too high for most surfaces, which favours the cooling of the air.

Outdoors experiment

Discussion (continued)

The difference between the measured and the simulated temperatures is relatively large for the external surface points (16, 20, 24, 26 and 30). This can be explained by:

1)

-The constant convective heat transfer coefficient ($8 \text{ W/m}^2\text{K}$) assumed. In reality the heat transfer coefficient depends on the variable wind speed, on the orientation and on natural convection. The coefficient seems underestimated for the southwest position and overestimated for the northeast position.

-2)

-The assumptions made for the infrared sky radiation for the vertical walls.

-3)

- A negligent fixing of a released thermocouple using a white tape caused the high difference ($10 \text{ }^\circ\text{C}$) for the external roof temperature (P30). Also at night the measured temperature on the roof is lower than the simulated one. Indeed during the night there is no wind and a low convective heat transfer coefficient (for downwards heat transfer) is most probably.

The relatively large differences for the external surfaces are damped out inwards through the thermal insulation. This damping effect is lower for the double glazing and indeed also on the internal glazing surface an underestimation of $5 \text{ }^\circ\text{C}$ occurs.

Outdoors experiment

Discussion (continued)

A good correspondence between measurement and simulation is found for the floor positions. Temporary temperature fluctuations due to the absorbed solar radiation occur in both measured and simulated temperature courses (for example positions 10, 11, 12 and 15). Also in the edge positions (3, 13 and 15) the correspondence is good.

The temperature courses in the positions 4, 5 and 6, compared to the ones in the positions 7, 8 and 9, show clearly that the effects of solar absorption, infrared radiation and 2D/3D conduction are simulated correctly.

It can be concluded that the correspondence between the measured and simulation temperature courses is good. The differences can be explained by the simplified empirical convection model, and by the inaccuracy of some of the boundary conditions. The simulation of the transient 3D heat conduction, the infrared and solar radiation, and the convection using the program VOLTRA allows reliable results.