373: Sustainability of retrofit actions in industrial buildings

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Abstract

Many manufactories in Italy are based in huge one-level buildings with extended flat roofs. In this kind of buildings very scarce attention has usually paid to insulation of envelope elements and heat losses through roof have the main part in the thermal balance leading to high energy demand. Even if Italian Regulation in the past till 2006 did not limit energy consumption in industrial buildings, many retrofit actions has been performed in order to cut energy costs. The most common action has been the insulation of roof with 6 to 10 cm of thermal insulation material covered by waterproof bitumen membrane. This latter layer characterized by an high absorption coefficient allows great quantities of solar radiation to penetrate into the roof multilayer so that materials, especially insulating ones, can be damaged by conspicuous thermal variations.

Authors, measured behaviour of temperature on a flat industrial roof during summer 2005. The roof temperature at different level was analysed and was pointed out insulation thermal stress in order to evaluate the durability of this material. Other envelope solutions are analysed comparing heat flow rates through the different roofs.

Keywords: thermal insulation materials, energy savings, industrial buildings

1. Introduction

In the North of Italy in the last decade the erection of industrial buildings has been a very important part of global new edifices. As an example in 2001 the number of new built manufactories represents the 34% on the total of new buildings. But if we look to volume occupied, the new manufactories represent the 66% of total new buildings.

Even if, only in 2006 Italian Regulation introduced a limit to energy consumption of this kind of buildings, many retrofit actions has been performed also earlier in order to cut energy costs. Considering that the most of industrial buildings are huge one-level buildings, thermal characteristics of roof are relevant in order to limit energy requests both during summer and heating season. That's why the most common action is the insulation of roof with 6 to 10 cm of thermal insulation material covered by waterproof bitumen membrane. This last bitumen layer can absorb great quantities of solar radiation so that materials can be damaged by huge thermal variations. Thermal insulation is, of course, the weakest material as far as durability is concerned and thermal stress may lead to quick ageing.

Some European standards [1] try to test materials under real conditions. In particular polyurethane is heated up to 70°C for 21 days in order to evaluate the mean thermal transmission coefficient during 25 years of operation. On the other hand real operational conditions can give rise to quick temperature variations that can become critical, especially if there are great solar irradiation. That's why during the year 2006 was set up an agreement between IUAV-University and BING (European Federation Rigid Polyurethane Foam Associations) concerning the measurements of temperatures at the surface and inside the insulating layer of two different kind of flat roofs.

Data collected have been used in order to tune a numerical model capable to estimate the temperature profile inside the roof structure. With the aim of a sensitivity analysis a series of simulations were performed and the temperature variations in different climatic conditions and for different kind of roof surface emissivity were compared. This analysis has been performed by means of the computer code HEAT2 (Version 5.0) by Lund – Gothenburg Group for Computational Building Physics in cooperation with Department of Building Physics (Lund University) and Building Technology Group - M.I.T. (USA).

2. Temperature measurements

2.1 Roof description and probes location

As a case study a flat roof covering a manufactory building situated in Padova (Italy, 45°24'N) was investigated. It was composed of a prestressed concrete slab, insulation layer and covered by two bituminous membranes. In table 1 are reported the thermo-physical properties of the different materials.

Four Pt100 thermal resistances (figure 1) have been used for temperatures measurement: 4 wires circuit are used for electrical connections. Two multichannel data logger (Data Taker 605) are used for data recording.

Meteorological sensors (DeltaOhm) allowed to record air temperature, air humidity, wind velocity, air pressure and the solar radiation (piranometer LP 02-10, class 1): portable PC was directly connected with the data logger and used for data storage. The temperature probes have been placed on external surface and inside the insulating layer, 3 cm deep. Two measure points were selected and the probes were marked as follow:

- T1: surface temperature (right side);
- T2: internal temperature of insulating layer (right side, 3 cm deep);
- T3: surface temperature (left side);
- T4: internal temperature of insulating layer (left side, 3 cm deep).

In order to reduce the radiative exchanges of the surface probes, the external probes have been covered by low emissivity layer. In order to reduce the contact losses, the probes placed inside the insulating layer have been fixed with the same kind of material composing the layer. No shadows from other buildings, chimneys or projections covered the sensors during the year.

Fig 1. T1 and T2 probes on the roof

Table 1: Physical properties of roof layers.

Stratigraphy	**Thickness [m]**	**Density [kg/m^3]**	**Thermal cond. λ [W/(m K)]**	**Specific heat [kJ/(kgK)]**
Basement	0,25	1800	0,9	0,90
Primer	0,001	600	0,17	1,8
Moisture barrier	0,003	1300	0,26	0,88
Air-blown asphalt coating (1,5 kg/m2)	0,004	1300	0,26	0,88
Insulation layer	0,060	35	0,03	1,40
Bituminous membrane	0,004	1125	0,17	1,47
Slated bituminous membrane	0,004	1000	0,15	1,2

2.2 Measurements analysis

The measurements continued throught winter 2005-2006 and spring and summer 2006. Measurements analysis brings to some considerations. The period July-August was the warmest. In this period the roof surface reach very high temperatures and maintain high values (near the maximum) for a long time during the day, around 2 or 3 hours. As an example during the 21st of July, a very sunny day, surface temperature has been about 70°C± 2°C from 11:55 to 15:15. Anyway also during a summer day medium sunny (the 12th July) high temperature values last for 2-3 hours. On the other hand during the late afternoon the temperature lowers very quickly giving rise to a step gradient of temperature.

It is possible to notice that inside the insulation layer maximum temperatures decrease: the probe T_2 records values around 50°C for 3 hours during the hottest days in July.

Table 2: Temperature measured values [°C]

	T_2	T_3	T_1	T_4
June 2006				
maximum	52.1	**68.6**	**67.5**	44.2
minimum	10.2	2.5	2.3	17.3
average	30.2	31.6	31.7	30.5
variation	41.9	**66.1**	**65.1**	26.9
July 2006				
maximum	54.2	**70.8**	**69.9**	46..3
minimum	20.0	12.8	12.6	24.8
average	34.2	35.5	35.4	34.8
variation	34.2	58.0	57..2	21.4
August 2006				
maximum	48.7	**66.1**	**65.5**	40.4
minimum	15.0	7.5	7.5	21.0
average	26.8	27.2	26.5	28.6
variation	33.6	58.6	57.9	19.4
September 2006				
maximum	46.2	**61.3**	**61.9**	39.6
minimum	15.4	7.2	7.4	20.7
average	25.8	25..5	25.4	27.6
variation	30.9	54.0	54.4	18.9

Table 2 shows the maximum, minimum, average temperature values from June 2006 to September 2006. For a better comprehension of the data, the values of temperatures higher than 60°C (and temperature variations higher than 60 K) have been put in evidence. It is possible to verify the high temperature differences measured during the summer months (from May to September) for both the covering surfaces. The maximum value measured in April (near 60°C) is reached for both sensors T1 and T3 (flat roof): the minimum values are minus than 0°C.

Table 3 shows the hourly temperature variations for the different sensors. Concerning the thermal inertia of the roof, the materials seem to be able to accept a strong thermal variation in a few time; the outdoor variations and a reduced thermal capacity support thermal losses and indoor overheating.

Table 3: Hourly temperature variation (July 21st, 2006)

	ΔT2	ΔT3	ΔT1	ΔT4	ΔTa
5 ÷ 6	-	0.5	0.4	-	1.3
6 ÷ 7	3	4.5	6	1.2	3.6
7 ÷ 8	4.6	8.5	9.2	2	3.8
8 ÷ 9	5	10.6	9.1	2.6	2.6
9 ÷ 10	4.1	10.1	9.2	2.7	2.0
10 ÷ 11	5.6	9	9.2	3.1	1.9
11 ÷ 12	3.9	7.3	4.8	2.6	0.4
12 ÷ 13	1.6	2.1	2.8	1.2	0.3

The high night irradiation has been measured in January (show the Table): as consequence the measured temperature values are decreased until -13 ÷ -14°C. Average values are measured always over 30°C (from 33°C to 39°C) and with high variations: inside the roofs the measured data show temperature variations near 40 K but the surface values overstep 50K. These temperature variations are also noticed at the separation surface between insulating layer and covering layer. As consequence, special attention shall be posed for the thermal and mechanical characteristics of materials and for the installation procedures.

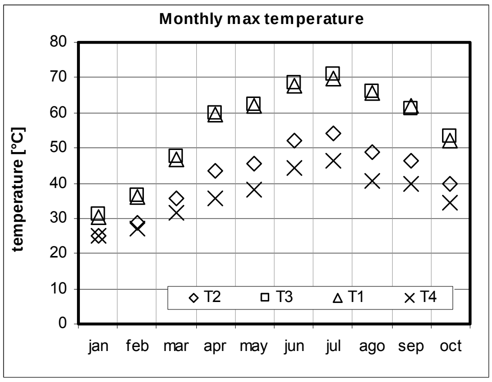

Fig 2. Maximum monthly temperature

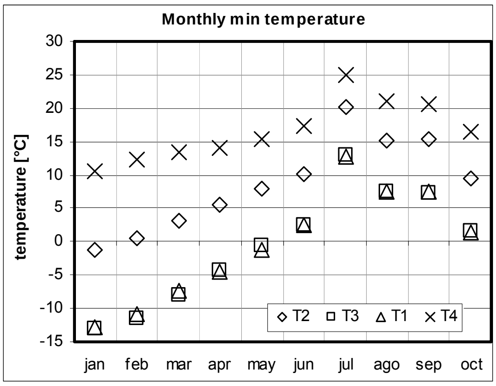

Fig 3. Minimum monthly temperature

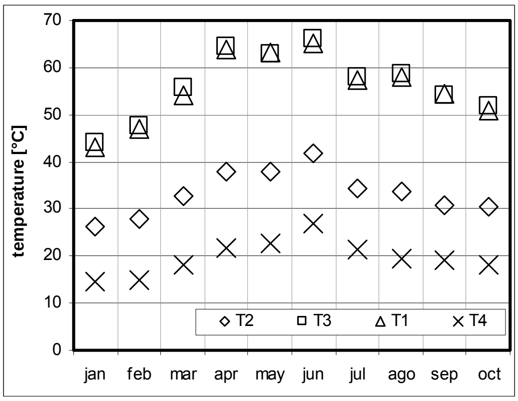

Fig 4. Temperature monthly variation

3. Simulations

3.1 Thermal model

If we apply the first law of thermodynamics (the law of energy conservation), we first need to identify a control volume dV, a region of analysed space bounded by control surfaces through which energy and mass can pass. The control surface and different layer will be identified with suitable thermal properties. The external surfaces shall be characterized by the absortivity a and emissivity ε and each layer with thermal conductivity λ, specific heat c and density d.

A general form of the conservation law of energy may be expressed on a rate basis as follows:

$$\dot{E}_{in}+\dot{E}_{g}-\dot{E}_{out}=\dot{E}_{st} \qquad (1)$$

$\dot{E}_{in} =$ inflow rate of energy [W/m^2]. It is a surface phenomena, this rate can be dependent on the solar irradiation G_{sun} by means of the absorption coefficient a:

$$\dot{E}_{in}=a\,G_{sun} \qquad (2)$$

$\dot{E}_{g} =$ rate of energy generated in the control volume dV. For this analysis we may put:

$$\dot{E}_{g}=0 \qquad (3)$$

$\dot{E}_{out} =$ outflow rate of energy [W/m^2]; in the case of a control volume placed in a roof, it may be considered as sum of heat flow exchanged by convection q_{conv}, plus the radiative heat flow q_{rad} (heat exchange with the surroundings) and the conductive heat flow q_{cond} (heat exchange with adjacent layer).

$$q_{conv} = h\,(t_s - t_\infty) \qquad (4)$$

$$q_{rad} = \varepsilon\,\sigma_n\,(T_s^4 - T_{ext}^4) \qquad (5)$$

$$q_{cond} = -\lambda\,\Delta t/\,\Delta x \qquad (6)$$

where:

The last term of the energy conservation law is the rate of energy stored:

$$\dot{E}_{st} = \rho\, c\, dV \frac{dt}{d\tau} \qquad (7)$$

In order to perform the heat balance on the analysed volume, the integration of each heat flow contribution shall be made on the whole considered portion of the roof; the solution of proposed equation will allow to calculate the temperature of the matter under time dependent (or steady state) conditions.

Both solar irradiation and outdoor temperature are imposed to be uniform and the time variation of these parameters is also considered to be uniform.

The heat flow rate by convection and radiation exchanged with the surroundings are calculated considering an external convective coefficient as $h_{conv,ext} \approx 10{,}0\ W/(m^2\ K)$ and the radiative coefficient equal to $h_{rad,ext} \approx 6{,}5\ W/(m^2\ K)$. The total heat flow rate may be calculated with a heat loss coefficient as $h_{tot} = 16{,}5\ W/(m^2\ K)$.

For the external surface, the solution of energy conservation law requests a third kind boundary condition that imposes the heat exchange and the outdoor temperature.

However, it is possible to consider the definition of sol-air temperature [2], [3] as useful way for the calculation of the energy conservation law for calculating the temperature values. The sol-air temperature is the outdoor air temperature that gives the same rate of heat exchange into the surface, $q_{w,ext}$.

The following equation can summarise this definition (imposing air temperature equal to sky temperature and $h_{tot} = h_{conv,ext} + \varepsilon\ h_{rad,ext}$):

$$t_{sun-air} = t_{air} + \frac{aG_{sun}}{h_{tot}} \qquad (8)$$

This definition of sol-air temperature has been used for determining the external boundary conditions taking into account both solar irradiation and outdoor air temperature. Because of the difficulty in their measurement, some inputs have been fixed, such as the surface emissivity and the surface heat exchange coefficient h_{tot}. In particular simulations results fit measurements data considering as input h_{tot}= 18 W/(m^2 K).

A second preliminary consideration shall be made for the indoor boundary surface. We suppose that the analysed structures are typical shed roofs: the industrial shed may be characterized by a considerable indoor air thermal stratification. The air temperature near the roof may be higher than in occupied zone that is not usually conditioned. It is reasonable to suppose that the convective heat exchange is not prominent. As consequence, the computer simulations have been performed referring to the indoor air temperature $t_{indoor} \approx 30$ °C.

3.2 Analysis

Using Padova real climatic data for the year 2006 it was possible to simulate the roof thermal behaviour, in order to compare simulation results to measurements data.

Experimental data were used in particular to tune the simulation boundary conditions: in particular the surface resistance on external layer and the absorption value of bituminous membrane. The combination h = 18 W/(m^2 K) and $a = \varepsilon = 0{,}9$ gives the best results as shown in figures 5 and 6.

The next step was the simulation of the same roof with different external coatings that means different absorption coefficient (from 0,1 to 0,9) and under three different climatic conditions. The localities chosen are Venezia (45° 26' North latitude), Roma (41° 53' North Latitude) and Trapani (38° 01' North Latitude). The simulation was performed for one week of July, because it is considered the worst condition.

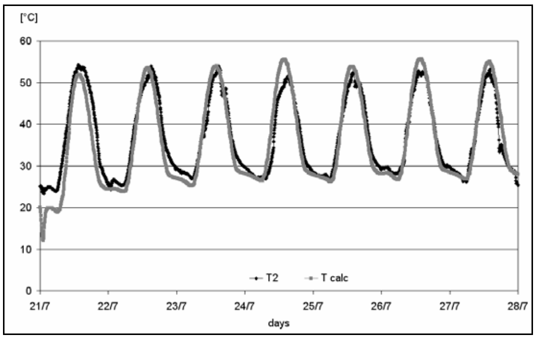

Fig 5. Comparison between internal temperature measured and internal temperature calculated

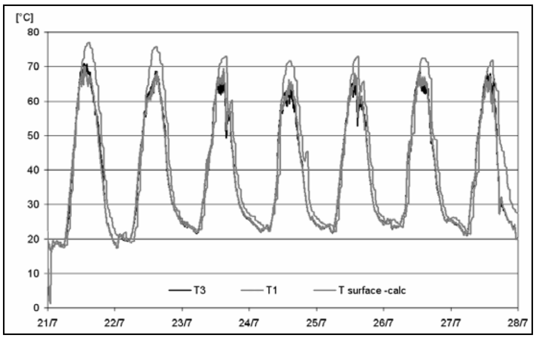

Fig 6. Comparison between surface temperature measured and surface temperature calculated

If absorption is 0,9 the maximum surface temperature reached is 72,5 °C in Venezia, 74,6°C in Roma and 81,5 in Trapani. These values decrease when absorption coefficient decreases (figure 7). In particular there is a linear correlation between maximum temperature values and absorption as shown in figure 8. Reducing absorption it is possible to cut maximum temperature for the 50 %.

As far as insulation thermal stress is concerned, temperature at different deeps was calculated: at the top of insulation, that means under 0,8 cm under roof top, in the middle (3,8 cm into the insulation) and under the layer, at 6,8 cm under roof external surface.

Even if the layer is width just 6 cm the temperature profile is very different from the top to the bottom. Temperature variations decrease when deep increases and maximum and minimum values are recorded with a phase shift (figure 9). Figure 10 shows maximum and minimum temperature inside insulation for different absorption of external layer: for low absorption the temperature keeps almost the same into the whole insulation thickness.

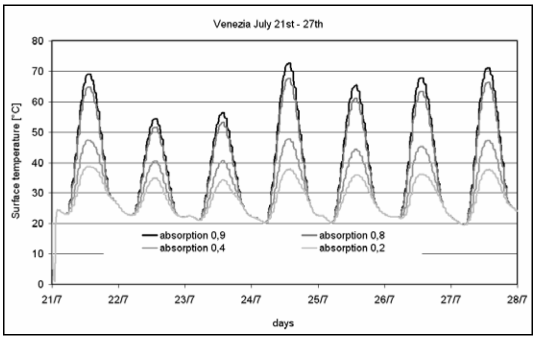

Fig 7. External surface temperature for different absorption coefficient. Venezia 21st – 27th July.

Finally the comparison of temperature in different location marks the high values of external surface which in Trapani, when a = 0,9, reaches 80°C for 61 hours in one week.

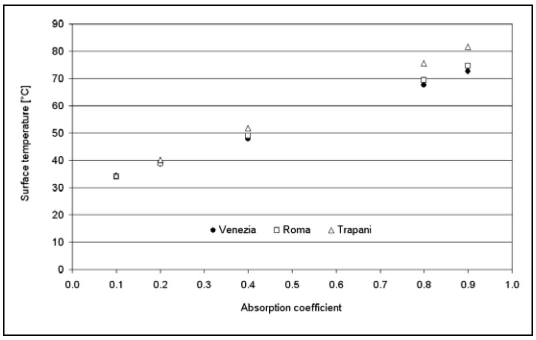

Fig 8. Maximum external surface temperature for different absorption and in different localities.

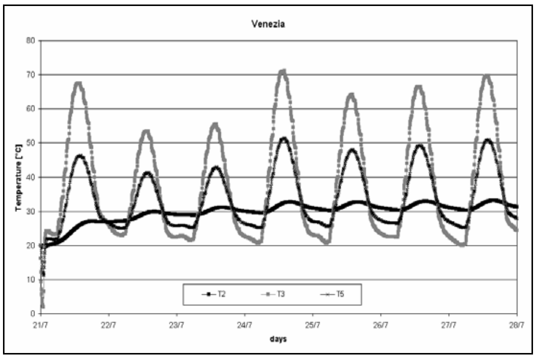

Fig 9. Temperature profile at 6,8 cm (T2), at 3,8 cm and at 0.8 cm under the external roof surface, during one week of July.

A way to limit heat flux entering and to reduce the surface temperatures can be the roof covered by vegetation obtaining a “green roof”. The potentiality of this arrangement in the reduction both cooling and heating load of a building is described in literature (for example [5], [6], [7]).

The specific layers added to a standard flat roof to obtain a green roof are the following:

- a soil layer, feeding nutritional elements and storing water for vegetation;
- a anti root barrier preventing the damage of the structure.

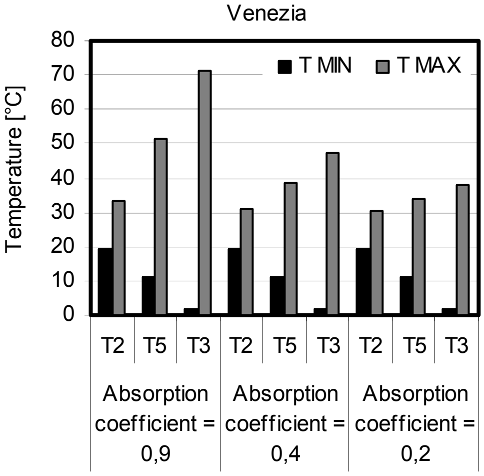

Fig 10. Temperature at 6,8 cm (T2), at 3,8 cm and at 0.8 cm under the external roof surface, for different absorption coefficient.

So at last a 30 cm thick soil layer covered by a extensive green carpet was added to the same roof previously analysed and the characteristics of added layers are reported in Table 4 [5].

For green covering layer an absorption solar coefficient 0,39 was assumed [5]. The effects of leaf shading and of transpiration were described using a modified sun-air temperature.

Table 4: Physical properties of green roof layers.

Stratigraphy	**Thickness [m]**	**Density [kg/m^3]**	**Thermal cond. λ [W/(m K)]**	**Specific heat [kJ/(kgK)]**
Saturated soil	0,2	1270	2,1	2,2
Wet soil	0,2	750	1,5	1
drainage	0,1	25	0,15	1,2
root barrier	0,003	1200	0,26	0,88
Waterproof. Sheet	0,003	1200	0,17	1,47

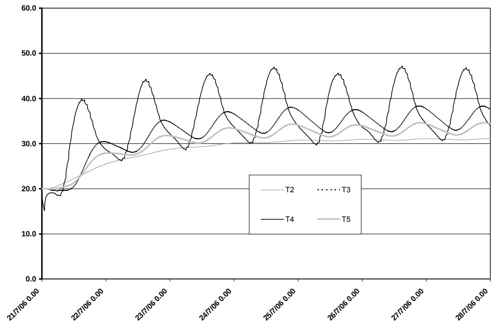

Fig 11. Temperature profile for saturated green-roof, during one week of July.

The temperature profile for the green roof has been evaluated for Trapani outdoor conditions: dry soil and saturated soil have been considered in order to take into account the different thermal properties of the materials. Figure 11 and 12 show the calculated values for a July week.

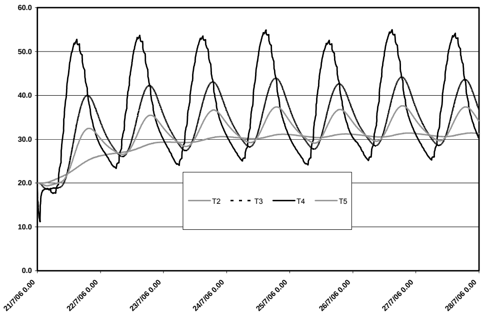

Fig 12. Temperature profile for dry green-roof, during one week of July.

Calculations performed for saturated roof show reduced temperatures variation: maximum surface values are near 45°C.

One day dynamic calculations allow to compare the values of thermal energy dissipated through the different roofs analysed in this paper:

saturated greenroof	dry greenroof	insulated roof
698.5 kJ	128.8 kJ	28.6 kJ

5. Conclusions

We can remark some considerations. First of all measurements shows that the average temperature range on roof surface is over 50 K during summer season (from June to September), so that more attention has to be paid on coupling joints in order to avoid crackling.

The thermal variations have a phase shift from external surface to internal (under the insulation layer) of about 4-5 hours, so it is not high. Measurement data were useful to numerical analysis in order to assign surface heat exchange coefficient. In particular boundary conditions were fixed tuning model with measurements. The temperature profile in Italian localities with high irradiation (Trapani) can give very high temperatures over 80°C with severe stress on the materials. An easy solution can be the use of high reflectance covering layer that can reduce both the roof temperatures and heat flow inside the building.

Green roofs structures can also be utilised for reducing the heat flow rates during summer and to restrict the indoor overheating. For Southern European climates, the choice of higher thermal capacities is very suitable for energy savings.

6. Nomenclature

a	absorption coefficient [-];
ε	emissivity [-];
ρ	density of the matter [kg/m^3];
λ	thermal conductivity [W/(m K)];
τ	time period [s];
c	specific heat [J/(kg K)];
dt/dn	temperature variation [K/m];
E_{in}	inflow rate of energy [W/m^2];
E_g	rate of energy generated in the control volume dV [W/m2];
E_{out}	outflow rate of energy [W/m^2];
G_{sun}	solar irradiation [W/m^2];
h	convective heat exchange coefficient [W/(m^2 K)];
h_{tot}	surface heat exchange coefficient [W/(m^{2}K)];
$h_{conv,ext}$	external convective coefficient [W/(m^{2}K)];
$h_{rad,ext}$	external radiative coefficient [W/(m^{2}K)];
$h_{conv,int}$	internal convective coefficient [W/(m^{2}K)];
$h_{rad,int}$	internal radiative coefficient [W/(m^{2}K)];
σ_n	the Stefan – Boltzmann constant = 5,67 $\cdot 10^{-8}$ W/(m^2 K^4)
t	temperature of the considered control volume [°C];
t_s	surface temperature of the considered control surface [°C];
t_∞	temperature of air beyond the boundary layer [°C];
t_s	surface temperature [°C];
t_{amb}	air temperature [°C];
t_{sky}	sky temperature [°C];
$t_{sun\text{-}air}$	sun-air temperature [°C];
T_{ext}	temperature of surrounding region [K];
T_s	surface temperature of the control surface [K];
Δx	thickness of the considered control volume [m]
V	volume [m^3]

7. Acknowledgements

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8. References

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