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LOW EARTH ORBIT NANOSATELLITE: INFLUENCE OF HEAT DISSIPATION ON PASSIVE THERMAL ANALYSIS

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Abstract.

The use of small satellites in ambitious missions presents challenges related to thermal breakdowns as one of the critical issues contributing to their failure. Heat dissipation and thermal management are still the major challenges in nanosatellite systems design. To meet the thermal stability requirements, it becomes statutory to manage passive and active thermal control to reach this goal while a variety of factors, such as high-powered components, sunlight and shadow on orbit, or a tight spacecraft layout, remain imposed.

A spherical nanosatellite thermal analysis was performed to show the effect of energy dissipation in a low earth orbit and the stability of the system with a special attention to batteries, which persist as the weak link among electronics parts. Additionally, a set of different material coatings was used to demonstrate their impact on the nanosatellite's thermal behaviour, hence highlighting their importance while designing such a spacecraft.

Keywords: Nanosatellite, thermal stability, material coatings, heat dissipation, passive thermal control.

1. Introduction

Satellites have always been developed to capitalise on the advantages that provide on all levels of weather monitoring, scientific observation, communication, remote sensing, and surveillance. The novelty with nanosatellites is that these favours are acquired at minimal costs [1–4]. Table 1 [5] clearly shows the benefits of the nanosatellite approach as compared to the traditional satellite approach when designing each satellite.

The need for a better thermal control on nanosatellites with temperature-sensitive components on-board requires many adjustments before launching. A simple shape of nanosatellites will narrow the range of temperatures experienced by internal components, and also outer irradiance coming from the Sun and the Earth if absorptance α and emissivity ϵ, which are the primary means of passive thermal control, are well-chosen, depending on the material used [8–14].

The objective is to sustain the temperature of all subsystems within their operating range. As each part of the satellite is coupled to the structure by conduction, the internal temperature is fairly uniform.

Therefore, the design of the thermal control system depends on the strictest temperature range, namely the batteries [0 °C, 40 °C] [15] and operating electronic equipment [−15 °C, 50 °C] [16].

The purpose of this paper is to establish a passive thermal analysis to ensure optimal operating conditions for inner components of a spherical nanosatellite, namely by keeping the temperature within the specified limits. The thermal analysis has been carried out with simulation tools based on the finite element approach for various coating materials, with consideration of heat dissipation in steady state conditions and, then also in nominal conditions. Obtained results were very promising, as, in outer space, the possibilities offered by a passive or even active thermal control should be considered to overcome the difficulties encountered, in particular for the sensitive parts of nanosatellites.

2. Materials and methods

2.1. Space thermal environment

The space environment in Figure 1 is very complicated and erratic; therefore, the simulation concerns modelling two extreme cases: The hot case, and the cold case. As their name indicate, those describe the most serious situations where thermal loads are relevant as indicated in Table 2 [17]. Since the orbit is Sun-synchronous [18] and circular at a 400-km altitude "98.13° inclination" with spacecraft pointing-earth, the β angle that determines the time during which the spacecraft is exposed to direct sunlight remains almost constant. When considering the Earth and its atmosphere as a whole, the calculation of the rate of absorption of solar energy, and the terrestrial infrared radiation emission averaged over a certain time

Design approach	Mission flexibility	System perfor-mance	Risk tole-rance	Deve-lopment time	Cost	System focus
Traditional/military	Low	High	Low	High	High	Performance
Traditional/commercial	Low	High	Low	High	High	Profit
Traditional/experimental	Low	High	Medium	Medium	High	Science
Nanosatellites	Medium	Low	Medium	Medium	Medium	Cost

Table 1. Comparison of traditional and, nanosatellite design approaches.

Parameters	Cold Case	Nominal Case [6]	Hot Case
Incident Solar Flux [W m^{-2}]	1317 Summer Solstice	1367	1419 Winter Solstice
Albedo Factor	0.22 at $\beta = 0°$	0.28	0.59 at $\beta = 90°$
Earth IR [W m^{-2}]	217	242	261
Heat dissipation [W] [7]	6.594	–	22.438
Temperature and Pressure		Vacuum at 2.7 K	

Table 2. Chosen conditions for simulation purposes.

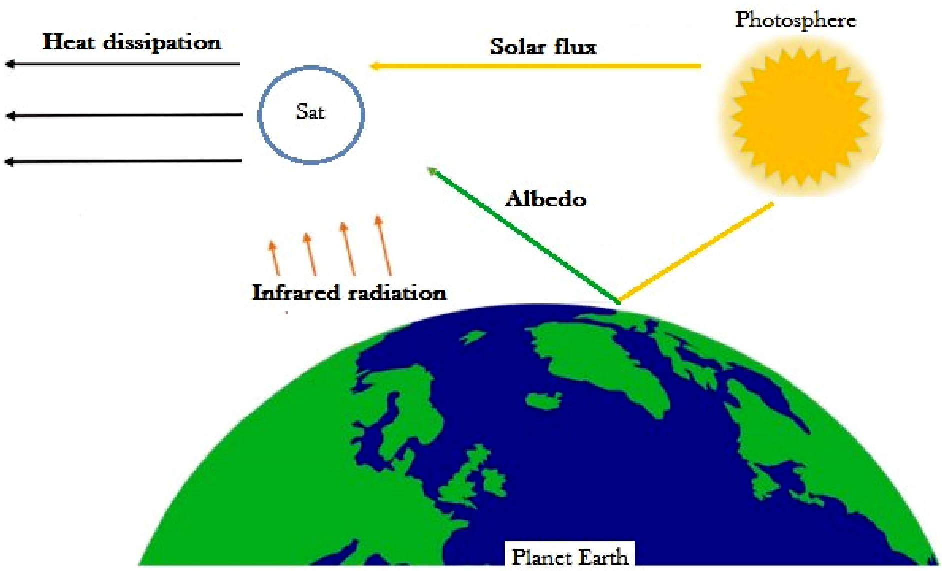

Figure 1. Nanosatellite heat exchange.

interval may unfold the radiative balance of the Earth with the Sun and outer space [19].

In low Earth orbit (LEO), the altitude is less than the diameter of the Earth and satellites can only see a small part of the Earth at any given time. This means that the conditions will change dramatically as the satellites move through different combinations of environments. These changes must be given priority in the design of the thermal control satellite system.

2.2. Thermal analysis

The primary objective of the thermal analysis is to ensure the preservation of the satellite's internal components within the specified temperature threshold, especially batteries as mentioned earlier. The steady-state thermal analysis, performed for the nanosatellite in Figure 2, is governed by the equation:

$$A_{sat} \times \epsilon \times \sigma \times T^4 = Q_{sun} + Q_{alb} + Q_{ear} + Q_{int}, \quad (1)$$

where on the left side of Eq. (1), A_{sat} [m^2] is the satellite's total area emitting radiation, which has the same external area as a Cubesat of 10 cm × 10 cm × 10 cm, ϵ [-] is the emissivity, σ [W m^2 K^{-4}] is the Stephan-Boltzmann constant and T [K] is the temperature required, however, on the right side Q_{sun} [W] is the heat input from the solar radiation, Q_{alb} [W] is the heat input from the Albedo radiation, Q_{ear} [W] is the heat transferred due to Earth Infrared, and

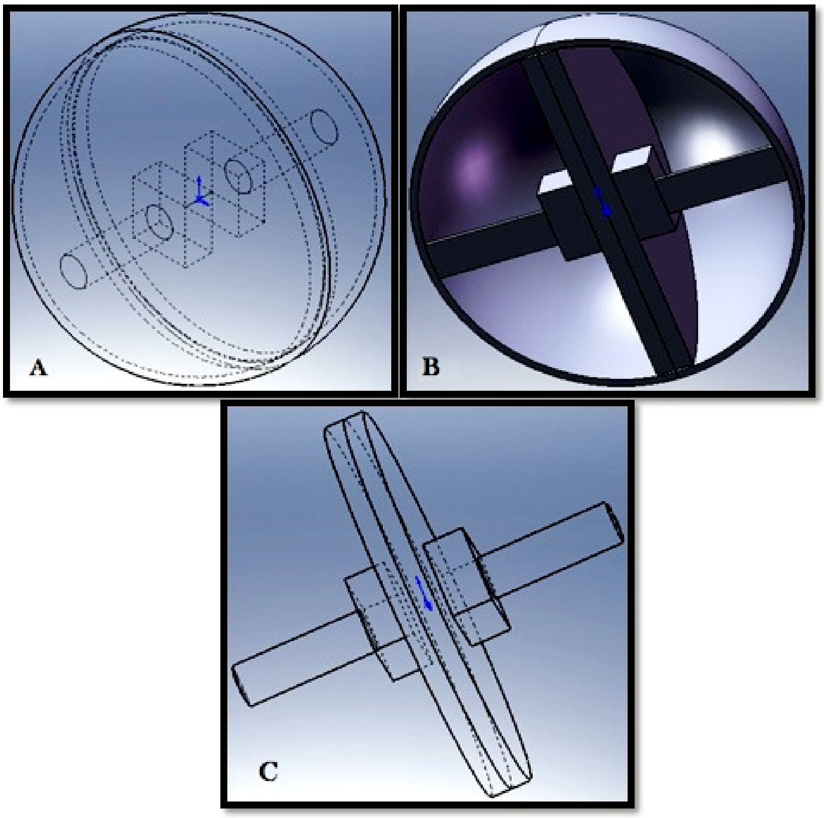

Figure 2. A: Panoramic view, B: Front plane section view, C: Inside view.

Q_{int} [W] is the nanosatellite internal heat load, which refers to the dissipated energy from the electronic components and batteries.

At this stage of analysis, the absorptivity factor α can't be remarked in Eq. (1), yet, dissecting Q_{sun}, Q_{alb}, and Q_{ear} terms clearly shows the impact of the absorptivity on the equilibrium balance. As a matter of fact, the three quantities are defined as follows, Eqs. (2), (3) and (4):

$$A_{sun} \cdot \alpha \cdot J_s = Q_{sun}, \tag{2}$$

where A_{sun} is the projected area receiving solar radiation, α is the absorptance factor, and J_s is the solar constant.

$$A_{alb} \cdot \alpha \cdot J_{alb} = Q_{alb}, \tag{3}$$

where A_{alb} is the projected area receiving albedo radiation, and J_{alb} is the intensity of the albedo radiation.

$$A_{ear} \cdot \epsilon \cdot J_{ear} = Q_{ear}, \tag{4}$$

where A_{ear} is the projected area receiving earth radiation, and J_{ear} is the intensity of the planetary infrared radiation.

As it can be seen in Figure 2, the main component of the nanosatellite, almost totally made of aluminium alloys, is a disc panel, where different electronic cards may be installed, and which is not dissipating power in the upcoming simulation. The disc panel is mounted in the equator enclosed by batteries, the most power-dissipating elements, that are supported by a double tube in the axis of spinning.

Coating	$\boldsymbol{\alpha}$	$\boldsymbol{\epsilon}$
Black Body	1	1
White Paint V200	0.26	0.89
Black Paint H322	0.96	0.86
Brilliant Aluminum Paint	0.70	0.13
Buffed Aluminum	0.16	0.03
Blue Anodised Titanium Foil	0.30	0.31

Table 3. Used coatings for the nanosatellite [23].

It is always accurate to process a perfect thermal, mechanical and electrical design of useful loads at the very beginning of the design process to avoid anomalies that may occur due to the details of the payload packaging. Indeed, there are many challenges that engineers face when designing a spacecraft, namely thermal ones that have made the subject of several research papers for the optimisation of such an analytical approach [20] and even experimental testing [21].

The passive thermal analysis, shown in Table 3, concerned multiple coating materials, in extreme conditions with heat dissipation, but also in nominal conditions with no heat dissipation as mentioned in Table 2. The temperature is calculated by finite element code in accordance with all the boundary conditions [22].

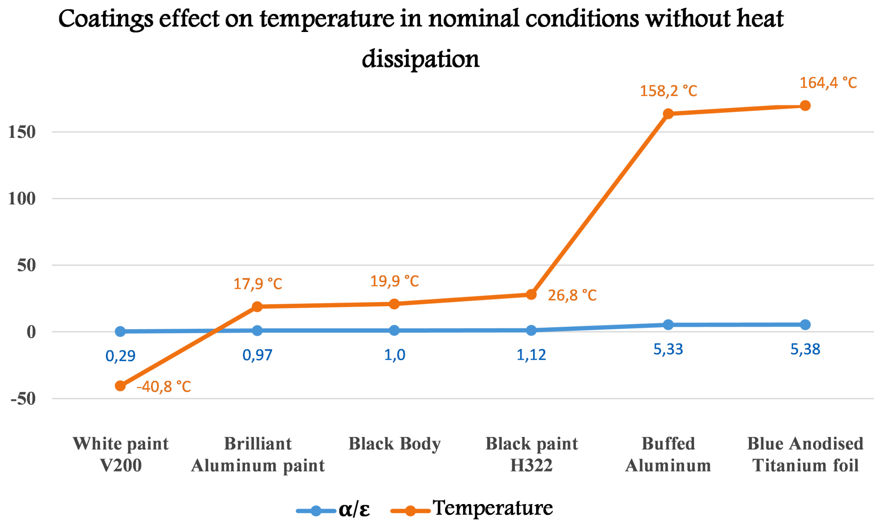

Figure 3. Coating effect on temperature in nominal conditions.

Coating	$\frac{\alpha}{\epsilon}$	Temp [°C]
White Paint V200	0.292	−40.8
Brilliant Aluminum Paint	0.967	17.9
Black Body (No coating)	1	19.9
Black Paint H322	1.116	26.8
Buffed Aluminum	5.333	158.2
Blue Anodised Titanium foil	5.384	164.4

Table 4. Temperatures in nominal conditions without heat dissipation.

Coating	$\frac{\alpha}{\epsilon}$	Min Temp [°C]	Max Temp [°C]
White Paint V200	0.292	13.4	15.4
Brilliant Aluminum Paint	0.967	55.1	57.0
Black Body (No coating)	1	56.7	58.7
Black Paint H322	1.116	62.4	64.3
Buffed Aluminum	5.333	186.5	188.3
Blue Anodised Titanium foil	5.384	186.8	188.6

Table 5. Min and Max temperatures for cold case simulation.

3. Results and discussion

3.1. Nominal case results

Referring to the temperature of the batteries, which should remain within the predefined ranges to maintain the proper functioning of the nanosatellite, we hardly notice that, under the nominal working conditions (Table 4 and Figure 3), three of the six coatings meet the above condition and allow the batteries' to run at acceptable temperatures, namely [17.887 °C, 19.901 °C, 26.848 °C].

For all the results obtained, the temperature of the batteries was the highest and the simulation made it possible to clearly identify the problem and try to start on a good basis when proposing solutions. All these coatings have an $\frac{\alpha}{\epsilon}$ ratio around unity.

For the report of the other coatings, it is obvious that other passive thermal controls should be considered, namely heat-conducting elements, adiabatic spacers, modifying the geometry of the spacecraft, or even active thermal control, but one must keep in mind that the latter should only be used when it is impossible to meet the requirements.

3.2. Cold case results

For the cold case simulation, Table 5 and Figure 4, it is clear that "White paint V200" perfectly follows the temperature required for the proper functioning of the nanosatellite, the three ratios of coatings that follow need only a complement of passive control to fall within the optimal operating temperature range of the batteries. However, for "Buffed Aluminum and Blue Anodised Titanium" coatings, an active thermal control is required because the temperatures have exceeded the limits.

3.3. Hot case results

Finally, for the hot case, Table 6 and Figure 5, the obtained results show that under the conditions defined at the outset, a temperature exceeding 200 °C is reached, and therefore another type of coating material must be applied in addition to an active thermal control to decrease the temperatures and ensure optimal operating conditions for the spacecraft.

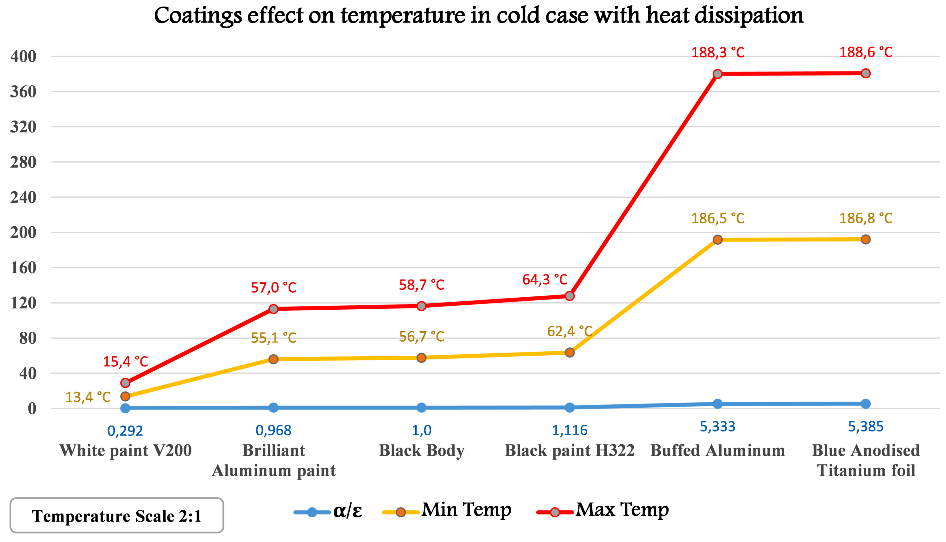

Figure 4. Coating effect on temperature in cold case conditions with heat dissipation.

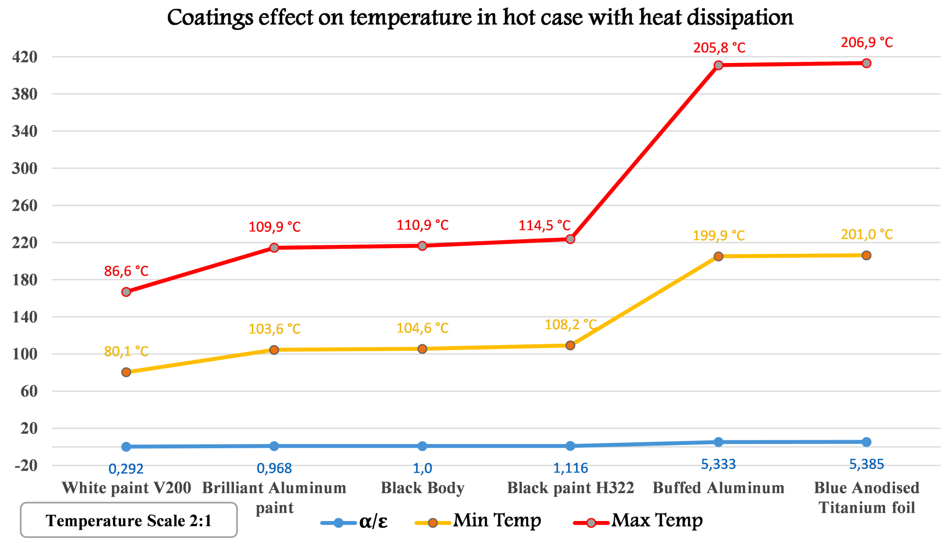

Figure 5. Coating effect on temperature in hot case conditions with heat dissipation.

Coating	$\frac{\alpha}{\epsilon}$	Min Temp [°C]	Max Temp [°C]
White Paint V200	0.292	80.1	86.6
Brilliant Aluminum Paint	0.967	103.6	109.9
Black Body (No coating)	1	104.6	110.9
Black Paint H322	1.116	108.2	114.5
Buffed Aluminum	5.333	199.9	205.8
Blue Anodized Titanium foil	5.384	201.0	206.9

Table 6. Min and Max temperatures for hot case simulation.

3.4. Batteries issues

As it can be seen in Figure 6 and Figure 7 taken from a cold and a hot analysis, the main cause of the high gradient of temperature is the battery “In red”, It is noteworthy that for an operational nanosatellite in the harsh conditions of the outer space, one should think about using all possibilities offered by passive thermal control, or even active thermal one, to overcome the encountered difficulties.

In addition to this, we can undoubtedly notice that the temperature distribution at the level of the different elements of the nanosatellite is almost the same in both extreme cases [24].

It is important to remind that only the dissipation of heat caused by the batteries has been involved, yet if other major parameters are involved in the system with the complexity of their heat dissipation, results will vary greatly.

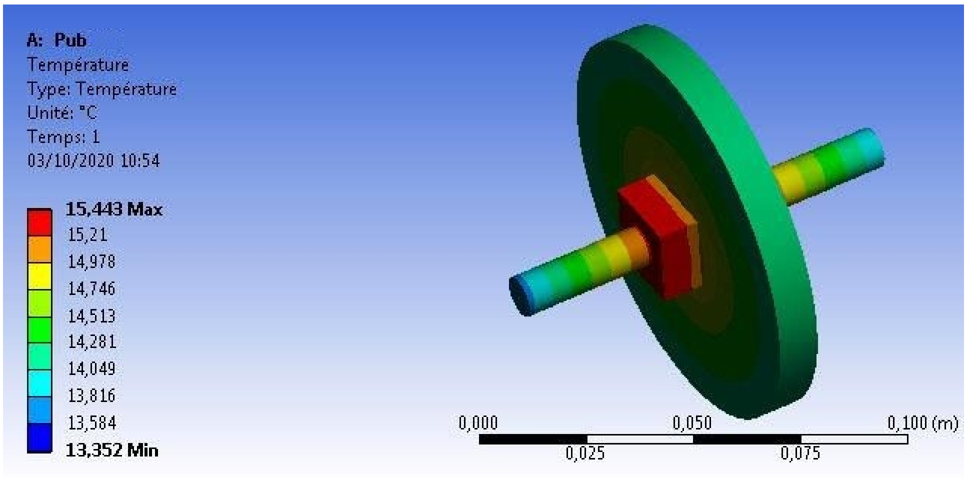

FIGURE 6. Cold case internal temperature distribution $\frac{\alpha}{\epsilon} = 0.29$.

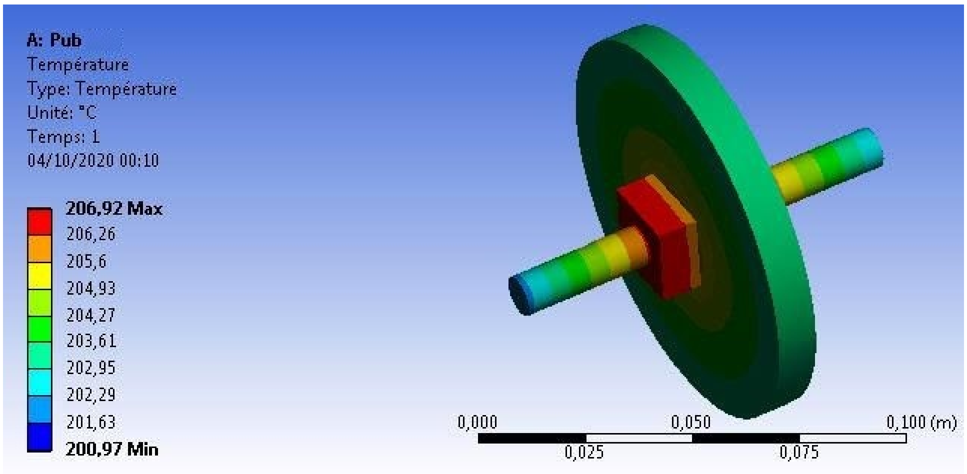

FIGURE 7. Hot case internal temperature distribution $\frac{\alpha}{\epsilon} = 5.38$.

4. Conclusions

Consistent design criteria for the development and comparison of several material coatings associated with heat dissipation parameters were presented. This paper went through a passive thermal analysis of a simply designed spherical nanosatellite. Indeed, it was assumed that the design provided has shown the effect of batteries' heat dissipation which imposed some changes in temperature plots. Even though, there is an extensive range of material coatings that can offer various $\frac{\alpha}{\epsilon}$ ratios, practical selection of the type of coating is often limited by the ageing characteristics. That's why one should think about using all the offered possibilities by finite element codes even those of active thermal control, which can be the subject of an extensive research study and may serve as an additional resolution tool for the current space revolution. An extended study must be performed to gauge the viability of that kind of thermal control, which may improve the quality and then the stability of that kind of nanosatellite.

List of symbols

α Absorptivity [–]
β Beta Angle [°]
ϵ Emissivity [–]
σ Stephan-Boltzmann constant $[\mathrm{W\,m^2\,K^{-4}}]$
T Temperature [K]

Q_{sun} Heat input from the solar radiation [W]
Q_{alb} Heat input from the Albedo radiation [W]
Q_{ear} Heat transferred due to Earth Infrared [W]
Q_{int} Nanosatellite dissipated energy [W]

A_{sat} Satellite total area emitting radiation $[\mathrm{m^2}]$
A_{sun} Projected area receiving solar radiation $[\mathrm{m^2}]$
A_{alb} Projected area receiving albedo radiation $[\mathrm{m^2}]$
A_{ear} Projected area receiving earth radiation $[\mathrm{m^2}]$

J_s Solar constant $[\mathrm{W\,m^{-2}}]$
J_{alb} Intensity of the Albedo radiation $[\mathrm{W\,m^{-2}}]$
J_{ear} Intensity of the planetary infrared radiation $[\mathrm{W\,m^{-2}}]$

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