Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 44 No. 5 (2023)

Satellite Temperature Modeling in Geostationary Orbit Using COMSOL

[1*]Shakila Hosseinzadeh Kondori, [2]Mustafa Helvacı
[1]*Department of Communication Systems, Istanbul Technical University, Istanbul, Turkey*
[2]*Assistant Professor, Department of Communication Systems, Istanbul Technical University, Istanbul, Turkey*
Corresponding Author: **- Shakila Hosseinzadeh Kondori**

Abstract: -In our world, communication satellites are becoming more and more significant. They are costly to create, launch, operate, and maintain, thus these costs are crucial. Due to the fact that electronic and satellite components can only operate within a limited temperature range, it is crucial to understand and manage the satellite's temperature in order to maximize efficiency both before and during the mission. This study considers GEO and comparable satellites with the goal of showing satellite temperature. We ignored the entire satellite's internal structure and focused only on the external heat generated by its surface (main body and solar panels). COMSOL is used in this project that is a simulation platform. Finally, the results have been displayed for the model at different times.

Keywords*: GEO, COMSOL, Satellite, Solar panel, Heat transfer, Radiation, Temperature, Simulation.*

1. Introduction

Satellites are playing a more and increasing role in our world. We have several distinct kinds of satellites: Earth observation and imagery, Communication and Navigation. Satellites can be found in low Earth orbit (LEO), medium earth orbit (MEO), highly elliptical orbit (HEO), and geosynchronous orbit (GSO), or geostationary orbit (GEO).

Only communication satellites in geostationary orbit will be taken into consideration in this research. A communications satellite is a man-made spacecraft that uses a transponder to relay and amplify radio telecommunication signals. It establishes a channel of communication between a source transmitter and a receiver situated at various points on Earth. Television, telephone, radio, internet, and military applications all use communications satellites. As you are aware that communication satellites are expensive to build, launch, operate, and maintain, therefore they are important. Understanding and managing the satellite's temperature is critical for optimizing efficiency both before and during the mission, because electronic components and satellite components can only operate within a limited temperature range. Additionally, each component of a satellite has its own lifespan, which is closely correlated with the material, temperature, etc. Therefore, thermal control and satellite thermal modeling can help us maintain maximum efficiency and know how long a satellite will last so that all of its components are kept within the appropriate temperature ranges. We considered GEO satellites with the goal of thermally modeling geostationary satellites.

Geostationary orbits are the orbits that communications satellites use to stay stationary in the sky with respect to viewers on the ground. They have an orbital period of one sidereal day, or roughly 23 hours, 56 minutes, and 4 seconds. Using the approximate form of Kepler's third law, the orbital radius is 42155 Km. Thus, when the radius of the earth (6370 km) is subtracted from the orbital radius, the altitude of the orbit is 35785 km. One geostationary satellite's vision covers around 40% of the earth's surface and the visibility of the Earth from a satellite in geostationary orbit is around 17°. A standard geostationary orbit has 0° of inclination and a period of 1436 minutes with 0 eccentricity.

1.1 Heat Sources

External heat sources are those that come from somewhere other than the system under examination. We describe the satellite as our system in this situation, thus external sources are those generated by the environment. As you may be aware, neither conduction nor convection occur in space. Because there is little matter in vast space, conduction occurs solely within the solar system. In order for convection to occur, a flow is required, which is not the case in deep space. Finally, just radiation and a little amount of conduction remain. There are three forms of radiation: direct solar radiation, albedo, and planetary flux, however planetary flux and albedo are negligible in GEO orbit.

a. Conduction

Heat conduction occurs as a result of various mechanisms in various media. It happens in a gas due to molecule collisions; in a fluid due to oscillations of each molecule in a cage formed by its nearest neighbors; in metals primarily due to electrons carrying heat; and in other solids due to molecular motion, which in crystals takes the form of lattice vibrations known as phonons. Fourier's law of heat conduction states that in a continuous medium, the conductive heat flux (q), is proportional to the temperature gradient [1]:

$$q = -k\nabla T$$

The thermal conductivity (k) is represented by the coefficient of proportionality and a positive value indicates that heat flows from high to low temperature regions. In anisotropic media such as composite materials, thermal conductivity can take the form of a symmetric positive-definite second-order tensor [1]:

$$k = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yz} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix}$$

b. Direct Solar Radiation

The sun is the primary source of energy in the solar system. Because it is so hot, it emits a great deal of radiation. As a result, it is directly accountable for direct sun radiation. The intensity ratings in the Solar System vary with distance from the Sun. Everything receives light at an intensity that is inversely proportional to the square distance from this star, which is a result of energy conservation (Figure 1.1).

It is crucial to consider the sunlight's intensity at Earth's average distance from the Sun. The solar flux is at its highest in winter and its lowest in summer because the intensity of the sun changes with its distance from the earth (Figure 1.2). This is caused by the elliptical orbit of our planet around the Sun. These days, the winter and summer solstices are when sunlight is at its strongest and least intense.

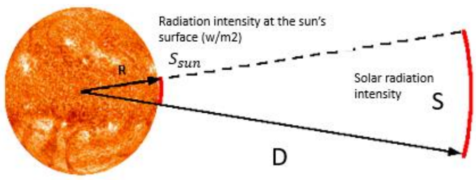


Figure 1.1: Solar radiation intensity [2]

Figure 1.2: Aphelion-perihelion [3]

In other words, a body's temperature influences the amount of radiation it emits; in fact, it is proportional to the body's temperature to the fourth power. The Stefan-Boltzmann law employs the Stefan-Boltzmann constant to provide the precise formula. The solar constant is the average energy flux from the sun at the mean orbital distance between the sun and Earth. The heat flux is approximately 1400 $(\frac{\mathrm{W}}{\mathrm{m}^2})$. If a one-square-meter panel is positioned in front of the sun with its surface normal to the sun's beams, it will receive nearly 1400 W of solar radiation. If a panel is one by-one-meter in size and faces the sun normally, it will produce 1400 watts per square meter.

In other words, the solar irradiance on an object some distance D from the sun is found by dividing the total power emitted from the sun by the surface area over which the sunlight falls. The total solar radiation emitted by the sun is given by σT^4 multiplied by the surface area of the sun $4\pi R_{sun}^2$ where R_{sun} is the radius of the sun (695×10^6 m).The surface area over which the power from the sun falls will be $4\pi D^2$. Where D is the distance of the object from the sun. Therefore, the solar radiation intensity, S in ($\frac{W}{m^2}$), incident on an object is:

$$S = \frac{R_{sun}^2}{D^2} S_{sun}$$

$$S \times A = \text{Solar flux on the desired section}$$

S_{sun} is the solar heat flux at the sun's surface ($\frac{W}{m^2}$) as determined by Stefan-Boltzmann's blackbody equation:

$$S_{sun} = \sigma T^4$$

Where:

Temperature of the sun is 5800 K. Stefan-Boltzmann' s constant (σ) is $5.67 \times 10^{-8}\ \frac{W}{m^2K^4}$. Thus, S_{sun} will be $64\times 10^6\ \frac{W}{m^2}$. Therefore solar radiation is $1400\ \frac{W}{m^2}$.

1.2 Heat Sources from Satellite

Each satellite located in geostationary orbit receives heat directly from the sun and radiates it in two ways: radiation to ambient space and surface-to-surface radiation. Surface-to-surface radiation is related to the main body of the satellite, and when we have radiation from one side of the body, the other surface of the body can absorb it. All surfaces and parts of the satellite can emit radiation into space. Also, the temperature of the space is considered to be 4 K.

2. Model

In Figure 2.1a, the schematic of the model drawn in COMSOL shows that the dimensions of the main body are 2.36 x 2.36 x 5.9 meters, and the span is 25.27 meters. This is a simple model without details, and only the two main parts of the satellite, which include the solar panels and the main body, are considered. The material of several components in Figure 2.1b (displayed in yellow) are Al-6062. In addition, the yellow parts in Figure 2.1c are gallium arsenide (GaAs).

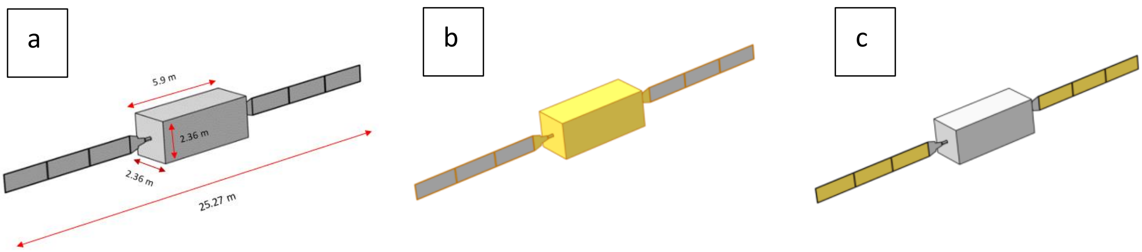


Figure 2.1: The schematic of the model

The properties of aluminum (Al-6062) defined in COMSOL are listed in the Table 2.1. Also, the properties of gallium arsenide (GaAs) can be seen in the Table 2.2.

Table 2.1: The properties of aluminum

Parameter	Value

Heat capacity at constant pressure (C_p)	714.8 $(\frac{\mathrm{J}}{\mathrm{kg} * \mathrm{K}})$
Thermal conductivity	150 $(\frac{W}{m * K})$
Density (ρ)	2810 $(\frac{kg}{m^3})$
Relative permeability	1
Electrical conductivity	3.774×10^7 $(\frac{S}{m})$
Coefficient of thermal expansion	23×10^{-6} $(\frac{1}{K})$
Young's modulus (E)	70×10^9 (Pa)
Murnaghan third-order elastic moduli (l)	-2.5×10^{11} (Pa)
Murnaghan third-order elastic moduli (m)	-3.3×10^{11} (Pa)
Murnaghan third-order elastic moduli (n)	-3.5×10^{11} (Pa)
Lamé parameter (λ)	5.1×10^{10} (Pa)
Lamé parameter (μ)	2.6×10^{10} (Pa)
Poisson's ratio (ν)	0.33

Table 2.2: The properties of GaAs

Parameter	Value and Unit
Heat capacity at constant pressure (C_p)	710 $(\frac{\mathrm{J}}{\mathrm{kg} * \mathrm{K}})$
Thermal conductivity	1260 $(\frac{W}{m * K})$
Density ($\boldsymbol{\rho}$)	**2000** $(\frac{\mathbf{kg}}{\mathbf{m}^3})$

Table 2.3: Input parameters [1], [4]

Parameters	Value
Thickness of satellite body	3 mm
Mesh Body Factor (A factor for mesh quality)	0.8
Number of mesh in thickness direction	2
Solar panels Efficiency	0.31
Cycle	86207 sec
Solar radiation	1400 $(\frac{W}{m^2})$

Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 44 No. 5 (2023)

Eclipse	4320 sec
Emissivity of solar panel	0.9
Emissivity of aluminum	0.5
Angle of solar declination on the south or north side in winter and summer	sin 23.5°
Reflectivity (default)	0.1
Absorption (default absorption by surface)	0.9
Space Temperature	2.7 K
Solar box reflectivity	0.5
Solar box absorption	0.5
Time step	20

The value of solar declination angle is +23.5 degrees during the summer solstice and -23.5 degrees during the winter solstice. It can be calculated by equation:

$$Sin\delta = 0.3979.cos[0.9856 * (N - 173)]$$

(N=number of days since January 1st, δ=declination angle)

3. Methods

3.1 Function of Surfaces

Each surface of the satellite body's radiation is evaluated independently. Each surface moves along a pattern determined by a function, allowing us to determine how much and when, or at what point in space, our satellite was exposed to sun radiation. We considered the zero and starting time to be the zero-degree point in orbit, which means exactly when the zenith surface is at its closest point and facing the sun. Also, the Nadir surface does not see any radiation and is completely behind the sun. In Figure 3.1, you see the satellite position at the starting point.

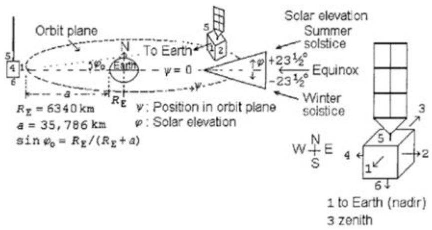


Figure 3.1: The satellite position [5]

This satellite has six main surfaces in its cubic body and two solar panels attached to the upper and lower surfaces [6]. Solar panels are designed to rotate. In other words, the surface of the solar panels always faces the sun. In this simulation, we have three important time periods in which thermal changes are significant. The first time period is from the starting point to the moment of entering the earth's shadow. The second time period is from the moment of entering the shadow of the earth to the exit zone, and finally, the third period is from the moment of leaving the shadow of the earth until reaching the starting point.

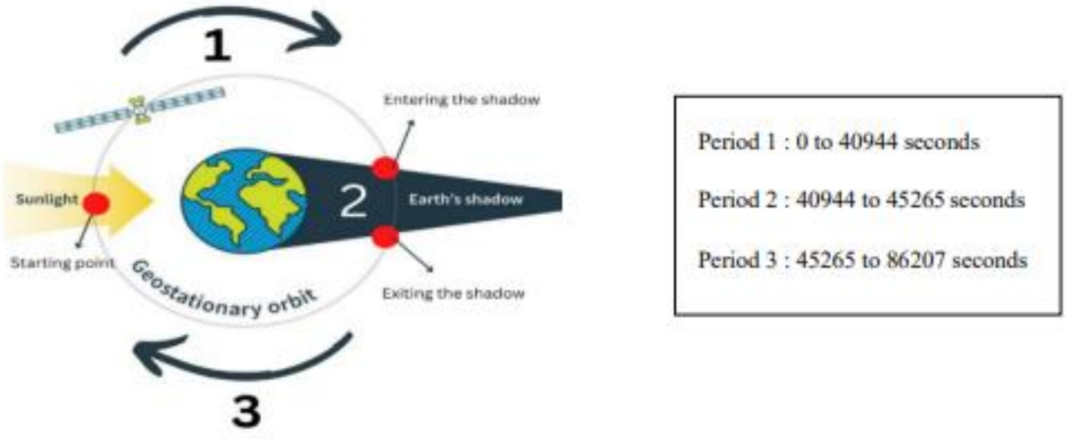


Figure 3.2: Important time periods

The surface of Zenith in the satellite is entirely facing the sun in the start, and it moves towards the $\pi/2$ point at a velocity close to that of the earth. Because of the angle it adopts, a lesser surface of Zenith is exposed to the sun's rays. After passing the point of $\pi/2$, we move to $3\pi/2$. The zenith's surface will be behind the sun and not exposed to the sun's rays. After passing through the point of $3\pi/2$, the Zenith surface gradually moves in the direction of the sun's radiation until it achieves its maximum solar flux. The function of the Zenith surface at various stages is depicted in the Figure 3.3.

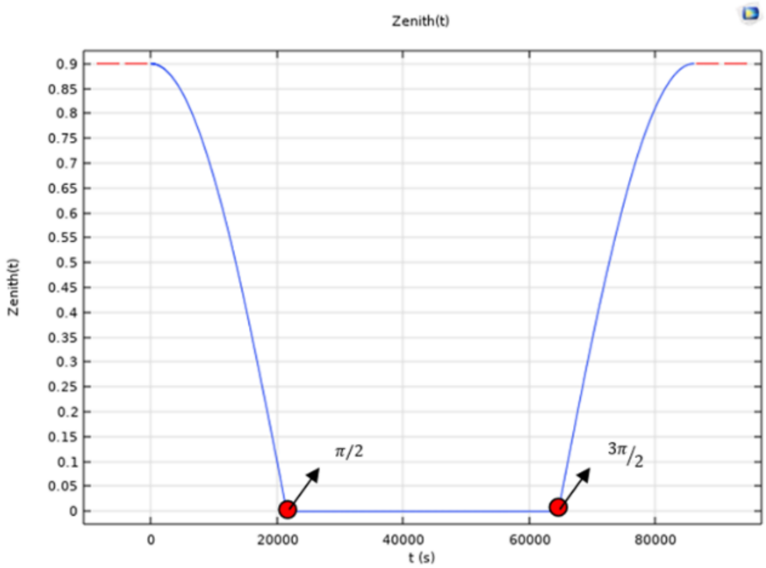


Figure 3.3: The function of the Zenith surface at various stages

Figure 3.4 depicts the function of each surface at various times.

Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 44 No. 5 (2023)

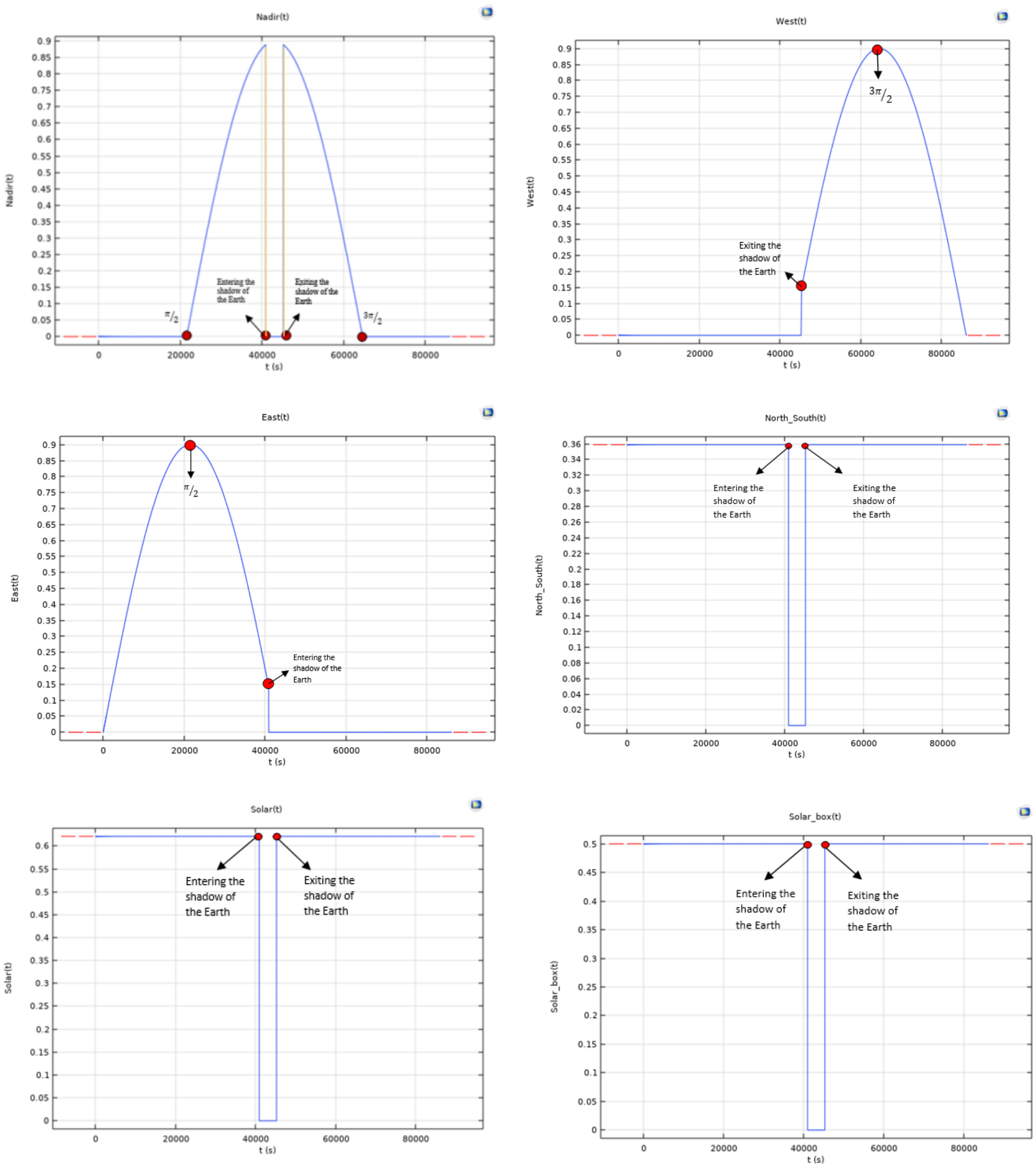


Figure 3.4: The function of each surface at various stages

We know that q_0 is the product of solar radiation in the function defined for each surface, and using these values, the general inward heat flux can be calculated for each surface [5].

$$-\mathrm{n}.\mathrm{q} = \mathrm{q}_0$$

$$\mathrm{q}_0 = \text{solar radiation} * \text{function of each surface}(\mathrm{t}) = \text{General inward heat flux}$$

3.2 Heat Transfer in Solids

The Heat Transport in Solids interface is used in this project to study heat transfer in solids via conduction and radiation. On all domains, a solid model is enabled by default. According to COMSOL Help [1], we simulate using the following equation. The values of each material were utilized for C_p, k and ρ. q is heat flux (conduction) and $\mathrm{Q}_{\mathrm{ted}}$ is the thermoelastic damping [1], [8].

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u.\nabla T + \nabla.q = Q + Q_{ted}$$

$$q = -k.\nabla T$$

$$Q_{ted} = -\propto T\colon \frac{dS}{dt}$$

$$-n.q = \varepsilon\sigma(T_{amb}^4 - T^4)$$

And for surface radiation to ambient [1], we use last mentioned equation. The values of each material have been used for surface emissivity. Also, space temperature (T_{amb}) is 4K. In addition, q is heat flux and T is absolute temperature. The equation of surface to surface radiation is [1]:

$$q = \varepsilon(G - e_b(T))$$

On the side of the boundary where the radiation is defined, where ε is the surface emissivity, G is the irradiation, and $e_b(T)$ is the blackbody hemispherical total emissive power. Where the radiation is defined on both sides, the radiative heat source is defined on both sides too.

3.3 Study

It is not possible to solve multi-physics equations for each part of the satellite and then couple them and solve them manually. In this project, with the help of COMSOL [7], [8], we first perform the meshing, identify all the involved and sensitive points, and finally, the temperature equations are solved for each part of the satellite and for the millions of lines and points on its surface, and then by coupling all the equations, the final results are obtained. It should be noted that the finer the meshing, the more accurate the results will be. Also, some parameters have a great impact on the simulation, such as the times we choose to display the temperature in this simulation.

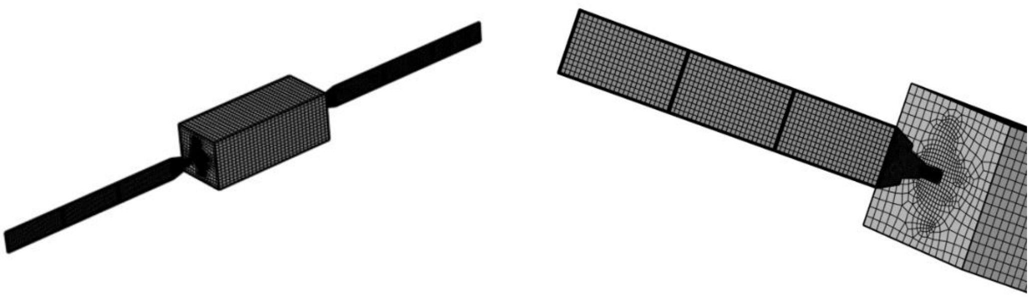


Figure 3.5: The result of meshing in COMSOL

4. Results

4.1 Solar Heat Flux on Surfaces

Figure 4.1 shows how much heat flux reaches each surface at any time. For example, when the satellite is completely facing the sun and at its closest point to it, the most heat flux reaches the zenith surface and solar panels.

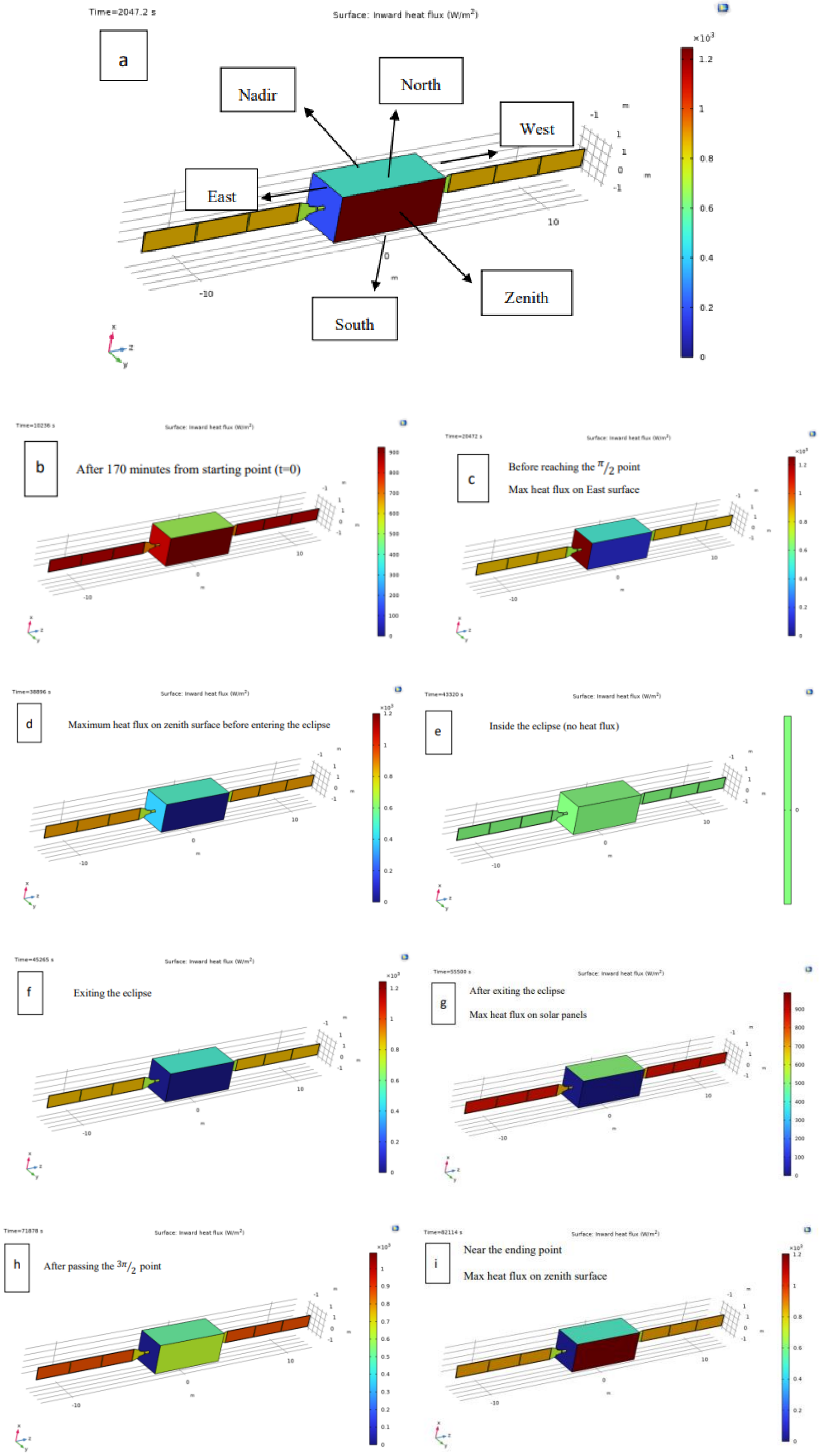
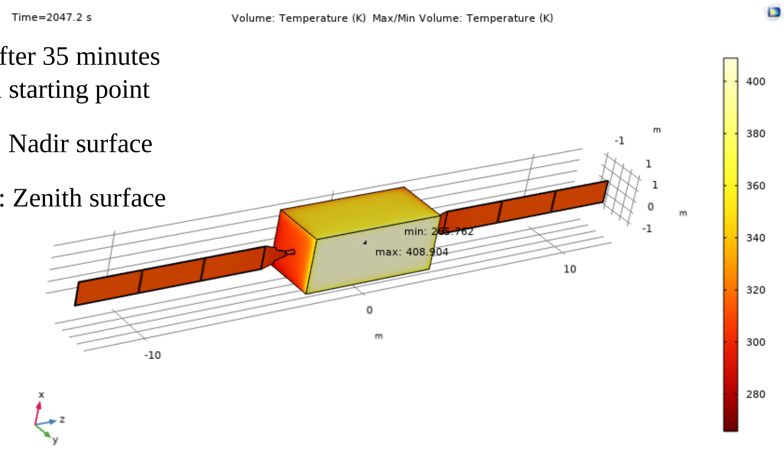


Figure 4.1: Solar heat flux on surfaces

4.2 Temperature of Satellite

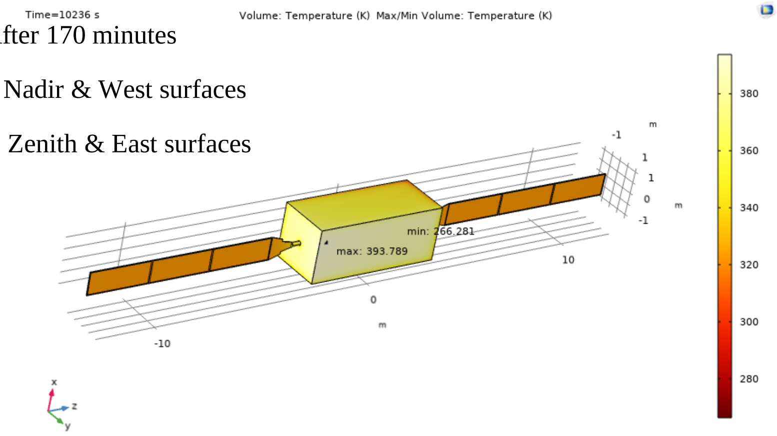
The temperature in terms of Kelvin has been simulated for each surface according to the heat transfer and the formulas used and their coupling in the COMSOL environment, and the results (considering highest and lowest temperature) have been displayed for the entire satellite at different times.



(a)After 35 minutes from starting point

Min: Nadir surface

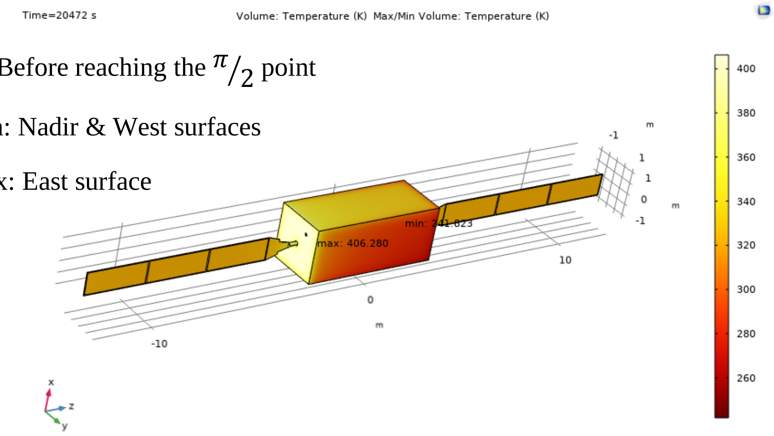
Max: Zenith surface



(b) After 170 minutes

Min: Nadir & West surfaces

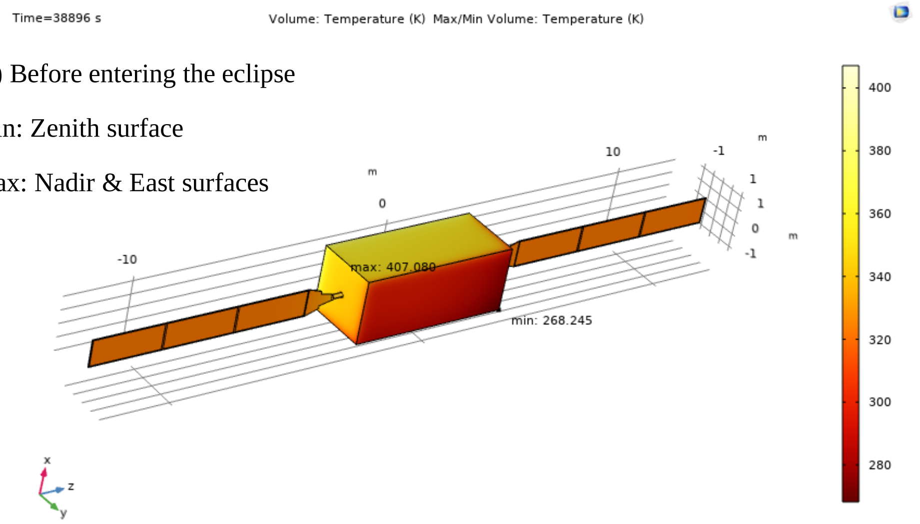
Max: Zenith & East surfaces



(c) Before reaching the $\pi/2$ point

Min: Nadir & West surfaces

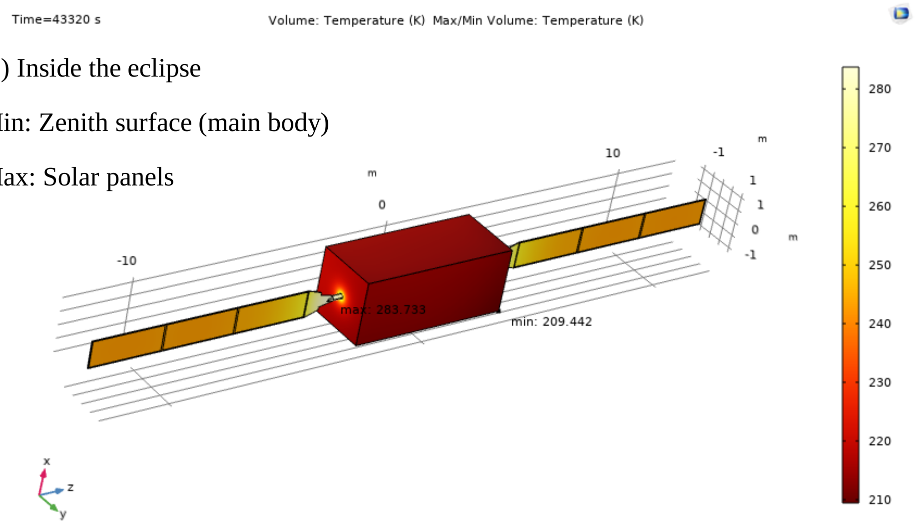
Max: East surface



(d) Before entering the eclipse

Min: Zenith surface

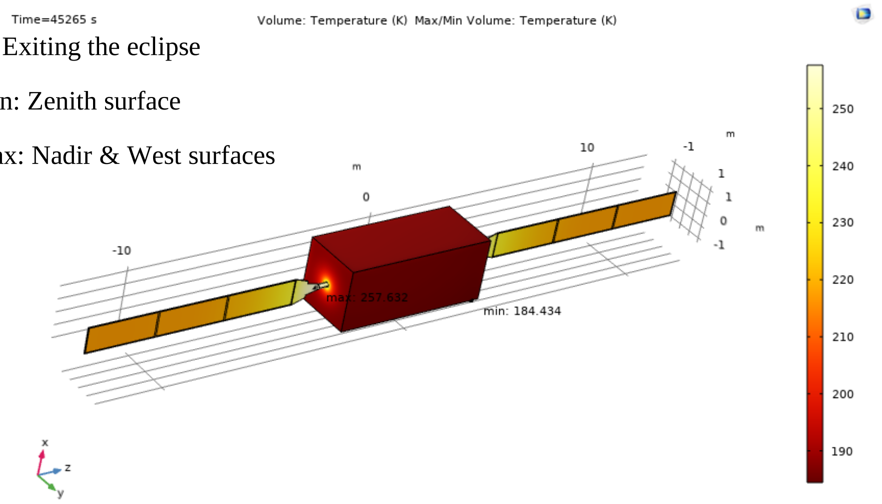
Max: Nadir & East surfaces



(e) Inside the eclipse

Min: Zenith surface (main body)

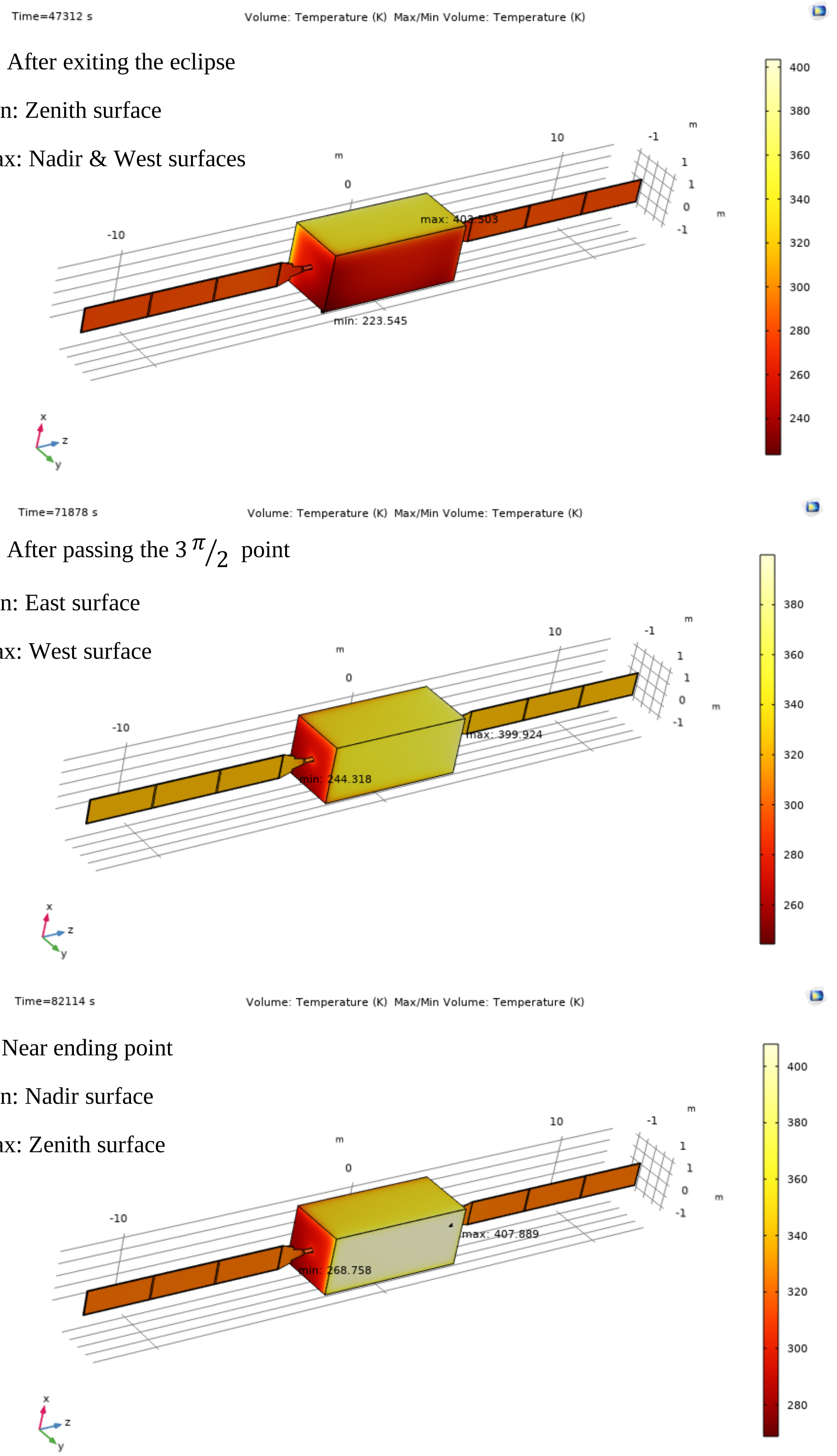
Max: Solar panels



(f) Exiting the eclipse

Min: Zenith surface

Max: Nadir & West surfaces



(g) After exiting the eclipse

Min: Zenith surface

Max: Nadir & West surfaces

(h) After passing the $3\,\pi/_2$ point

Min: East surface

Max: West surface

(i) Near ending point

Min: Nadir surface

Max: Zenith surface

Figure 4.2: Temperature of each surface (considering minimum and maximum)

5. Conclusion and Discussion

In this project, the main goal was to obtain the temperature of the satellite during one day, i.e., a complete round of the satellite in orbit. This satellite consists of two main parts (the body and the solar panel), which we examined. We omitted the internal parts of the satellite body. We obtained temperature diagrams in each part and at any time of the circuit by using the COMSOL Multiphysics environment and coupling the heat transfer equations.

A very important point is that the temperature changes are different in the three main time periods. These time intervals are: from the starting point to reaching the shadow of the earth; the time when it is in the shadow of the earth; and the time when it leaves the shadow of the earth and reaches the end point. One round of the satellite in its orbit is approximately 86207 seconds, and as mentioned before, the time it stays in the shadow of the earth is 72 minutes, or 4320 seconds. By subtracting this time from the total time, the time of entering and exiting the shadow can be approximately calculated. The moment the satellite enters the earth's shadow is in the 40944th second from the start of its movement (the point where time is zero). The moment the satellite leaves the earth's shadow is in the 45263rd second from the start of its movement.

According to the obtained results, the minimum temperature of the whole satellite is approximately 184.4 K, where the time from the starting point is 45265 seconds, and the maximum temperature of the whole satellite is 410.5 K, where the time is 84161 seconds. As you can see, the coldest point is when the satellite is leaving the shadow, where the time is 45265 seconds. When the satellite is closest to the sun and facing it, it is at the hottest point, which is at the end of its path.

In the other words, the point where the satellite is leaving the shadow of the earth is the coldest possible state of the satellite. We should control and consider this zone that satellite is in earth shadow and it is in coldest state.

If we want to consider only the eclipse time, the minimum and maximum temperatures of this satellite at the moment of entering the eclipse are 257 and 331 K, respectively. Also, at the moment of exit, the minimum and maximum temperatures are 184.5 and 257.63 K.

As a result, the main goal of this project is to show temperature of satellite and significant data (including maximum and minimum temperatures, solar heat flux at any level and at any time). By gathering this data, it is possible to calculate the satellite's life expectancy and more precisely plan for the maintenance of the satellite in orbit. The best design and calculation of the high temperature control system as well as the estimation of the satellite's life are greatly aided by performing this simulation process prior to the satellite's launch into orbit.

Refrences

[1] Heat Transfer Module Users Guide. COMSOL.

[2] Valverde Sacristán, Alejandro José. “Thermal Control in Space: Heat Sources | Tech for Space.” Thermal Control in Space: Heat Sources | Tech for Space, 25 May 2016, www.techforspace.com/spaceflight/thermal-control-heat-sources.

[3] Url-3 <www.almanac.com/content/what-aphelion-and-perihelion>, Aphelion-perihelion. Accessed 11 Oct. 2022.

[4] Url-4 <www.solar.com/learn/solar-panel-efficiency>, “Solar Panel Efficiency - Pick the Most Efficient Solar Panels Archives.” Solar.com, Accessed 29 Dec. 2022.

[5] Paul Zarchan, “SATELLITE THERMAL CONTROL FOR SYSTEMS ENGINEERS.” Progress in Astronautics and Aeronautics, vol. 181, 1998.

[6] Meseguer, J., et al. “Spacecraft Thermal Control.” WOODHEAT PUBLISHING IN MECHANICAL ENGINEERING, 2012.

[7] Tabatabaian, Mehrzad. *COMSOL 5 for Engineers (Multi-physics Modeling).* 2015.

[8] Mayboudi, Layla. *Heat Transfer Modelling Using COMSOL*. Mercury Learning and Information, 2018.