Comparative Study of Active and Passive Thermal Control Systems: A Case Study of Terra Satellite

Ritvika Tripathi

Student, Gems Wellington International School, Dubai, United Arab Emirates

Abstract: ***This paper examines the thermal control systems used in satellites, comparing active and passive methods. Active systems rely on energy to function, while passive systems operate without energy inputs. Through a case study of the Terra satellite, the article explores the advantages, limitations, and optimal applications of each system. A hybrid approach is suggested as the most efficient solution, as demonstrated by Terra's longterm use of both systems.***

Keywords: thermal control systems, active cooling, passive systems, satellite technology, Terra satellite

1. Introduction

Space is an extreme environment, which can heat and cool rapidly. Therefore, satellites that must function in this harsh climate for prolonged periods can sustain damage to equipment and wiring if the isolated system of the satellites is not temperature regulated [1]. Therefore, all satellites launched into orbit in space have some form of the thermal control system, which ensures that the satellite is regulated at an ideal temperature for payloads [2] that work at lower temperatures and to prevent damage caused to physical structures, misalignment of optical systems etc. due to large temperature differences. Generally, two types of thermal control systems are integrated into satellites: active and passive systems. Active systems being thermal control systems that use moving fluids and mechanisms [3]. Conversely, passive methods do not have any mechanically moving fluids or parts [4]. The purpose of this study is to compare active and passive thermal control systems and assess their effectiveness for satellite applications through a case study of the Terra satellite. This study highlights the importance of efficient thermal management in satellites, balancing cost, energy consumption, and reliability for long-term missions.

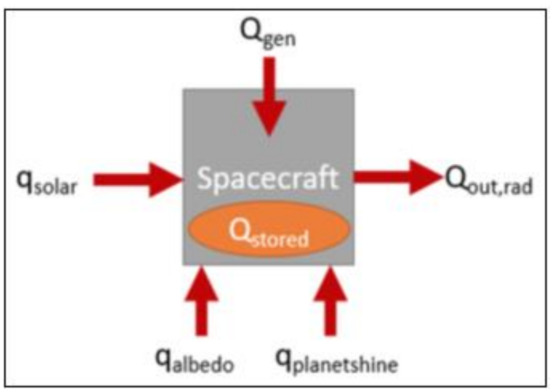
2. Background

Satellites must endure harsh climates in space, where temperatures can range from -170°C to +120°C [5]. The absence of a medium in space complicates matters of transferring heat. In a vacuum, conduction, and radiation are utilized by a satellite, with convection being impossible as it involves the movement of particles. However, with active thermal control systems which use power, they can be used to transfer heat through fluid movement. Hence, making convection within a satellite possible [6]. Given the nature of space, satellites are exposed to direct sunlight from the sun, which can cause a dramatic rise in temperature on surfaces facing the sun, however, the shaded regions could reach very low temperatures. Therefore, the sides facing the sun are areas of net gain for heat as heat gets transferred into the system, and the sides facing away from the sun are areas of net loss as heat dissipates out of the system [7].

The thermal conditions around a satellite depend on multiple external factors such as orbit, solar flux (determined by proximity to the sun), duration of a mission, and albedo (solar heat reflected off by a planet). Additionally, there are internal factors such as heat generated by a spacecraft and heat stored by an aircraft. The equation below shows all the balancing forces that help determine the solar environment of a satellite [2].

$$q_{solar} + q_{albedo} + q_{planetshine} + q_{gen} = Q_{stored} + Q_{out,rad} \quad \{1\}$$

In equation {1} Q_{solar} is the heat absorbed by satellites from the sun based on solar flux. Q_{albedo} is the solar heating absorbed based on the surface of a planet, the surface area viewing the planet and the absorptivity of the surface. $Q_{planetshine}$ is the infrared heating from a planet, which is based on the surface emissivity and, the surface area facing the satellite. Q_{gen} is the power generated and is based on the dissipation of heat from components within a satellite. For the energy that is stored by the satellite Q_{stored}, it is based on the thermal capacitance of the satellite. Finally, $Q_{out,rad}${heat radiated off the satellite} includes area designated for radiation, IR emitted and also other components that may not be designed to radiate but still dissipate heat.



The total heat radiating of the surface is calculated using the following expression [8]:

$$Q = A\varepsilon\sigma T^4 \quad \{2\}$$

Where,
Q = Energy
ε = Emittance
σ = Stefan-Boltzmann constant
T = Absolute temperature

As previously mentioned, heat within the satellite's systems is generated through its electronic components and batteries and is also transferred through external factors such as albedo and solar flux. To balance the total heat, satellite systems employ active and passive thermal control methods.

3. Thermal Control Methods

By definition, any thermal control directed via moving fluids or mechanisms, or power is classified under Active thermal control systems (ATCS)[3]. ATCS involves the mechanical pumping of fluids and powering heat transfer components to employ radiation, conduction and convection. This allows the satellites to maintain a target temperature of all components in the varying conditions of space.

Within the ATCS, there are multiple components that help regulate heat transfer in the system. Some of the common components are detailed below:

1) Heaters: Electric heaters are placed in areas prone to substantial temperature drops, therefore, whenever a component's temperature decreases beyond a threshold, the heater can increase the temperature of the component. Better conductive heating material is installed in areas that require higher temperature to operate or heat at a slower pace, where heat that has been generated from other components is conducted using conductive fluids or pipes [9].
2) Pump & Fluid loops: these are pipes that transport coolant throughout a satellite to reduce the temperature of components and dissipate heat from sensitive components to prevent overheating from interfering with functions. This system includes a pump for fluid movement; a heat exchanger, a system that transfers heat from one fluid to another; a space radiator, a device which regulates heat loss to prevent overheating [10].
3) Thermoelectric coolers: also known as the Peltier coolers, work on the principle of the Peltiers effect, where heat is transferred from the cold side to its hot side through a supply of external electrical energy [11].

Active thermal control systems have several advantages related to their usage. Firstly, ATCS provide more consistent precision in temperature control as they actively manage the input and output of heat. The precision in measuring and controlling temperature is imperative for the efficient performance of all components within a satellite system that are prone to damage given the temperature fluctuation. Secondly, ATCS can adapt to variations within the thermal environment of space. For example, different sides of a satellite either face the sun or are in shadows at different times, therefore, active systems heat, or cool components based on its real time demand.

On the other hand, there are certain disadvantages of implementing active thermal control systems in a satellite. Firstly, ATCS require a power source to operate all components that are part of the system. The energy required to maintain a system is a considerable constraint given its limited supply on spacecrafts in space. Additionally, the higher the demand of energy, which is supplied through batteries, the higher the increase in mass of the satellite: ultimately increasing the cost of launching a satellite. Secondly, as the ATCS uses mechanical and electrical parts, which makes it an active system, hence, it is prone to malfunctioning given its complex nature. With a chance of failure, ATCS are unreliable to some extent, and can for example, overheat or freeze components.

Passive thermal control methods, unlike ATCSs, require no mechanical parts or involve the movement of the fluids. These methods utilize natural physics laws of radiation and convection to dissipate or store heat, they also heavily depend on the materials properties and placement within the satellite.

Multiple components are classified under a PTCS. A few examples are detailed below:

1) Thermal switch: a device placed between heat producing components and heat transferring components, as heat reaches a certain threshold, the switch detaches from the heat conducting component[2].
2) Multi-layer insulation: lightweight insulation systems that prevent heat loss in the cold and deflect heat entering a system in a satellite. They work on the basic principle of thermal resistance in vacuum, where multiple layers of radiative sheets reflect in the opposite direction of heat flow [12].
3) Highly reflective material: their role in a PTCS is to eject waste heat energy with the use of radiative transfer principles, which is the transfer of heat without the presence of a medium. The emittance power of a radiator depends on its materials; therefore, all surfaces are given finishes with maximized IR emittance [13].

The PTCS has its own benefits when being applied to a satellite system. As PTCS require no external power source, it reduces the chance of malfunctioning parts, making them suitable for longer projects that cannot afford faults and power consumption to fix thermal systems due to limited supply. Secondly, passive thermal control systems require no energy even to fulfill its role of regulating temperature in a Satellite. The feature also lowers the power consumption within a satellite, which can be conserved for other functions within a satellite.

However, PTCS also have limitations with their performance. Due to their simplicity, PTCS have limited adaptability to variation in thermal environments. Moreover, as the passive system does not consist of fine-tuned instruments that can accurately reach a target temperature, therefore, the PTCS can only maintain stability within a system but cannot cater precisely to the dynamic changes in the temperature of surfaces of satellites in space.

4. Case Study of Terra

Terra is an earth observation satellite that was launched into lower earth orbit on December 18th, 1999. The spacecraft has a mass of 5,190kg and dimensions of 6.8m long and 3.5m across [14]. Each satellite has its own purpose, requirements and constraints, which determine the type of thermal control system that would suit the mission the most. For the purposes of this comparative analysis, the case study of the Terra satellite will be compared. Appropriateness of Thermal control systems vary based on the demands of a project. ATCS are usually applied to short-term projects, given conserving energy is not the biggest concern. Conversely, for Terra, that have long term missions like observation of Earth in the Lower Earth Orbit for a prolonged period [15]; PTCS are more suitable to avoid over consumption of power within a satellite as energy is a scarce resource, with only a limited amount that can be carried. However, as Terra orbits close enough to remain under Earth's shadow for a period of time, it has also been strategically engineered with active systems such as capillary pumped heat transport systems [16] and cryocoolers near temperature-sensitive components within the satellite to prevent temperature from reaching critically low or high levels.

All space missions have a budget determined within which engineers have to devise the best possible components and instruments for thermal control while minimizing cost and maximizing effectiveness. Generally, ATCS are higher in cost compared to PTCS due to the complexity of the components and the highly demanding maintenance [17]. However, as helpful as the extensive nature of ATCS is, PTCS are mostly suitable due to cost constraints in projects like Terra that must operate over twenty years. They are cheaper to develop and require near to zero recalibrations, therefore less likely to jeopardize a long-term mission.

5. Conclusion

Both active and passive thermal control systems are vital for satellite missions, each offering distinct benefits. While ATCS provides precision, PTCS ensures reliability over time. A hybrid approach, combining the strengths of both systems, has proven effective, as demonstrated by the Terra satellites continuous operation for two decades. Future missions can benefit from this dual strategy by balancing energy consumption and cost.

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