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Minimal-heating thermal management design for low-mass, power-constrained Tumbleweed mobile impactors on Mars

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Abstract

As we look to explore deep space, the development of cost-effective and low-mass solutions is becoming increasingly important. One example is the Tumbleweed mission, a low-cost Mars surface mission generating novel datasets by a wind-propelled circularly symmetrical surface exploration spacecraft swarm.

However, such rovers present unique challenges, particularly in terms of thermal management due to stringent mass and energy constraints, and a high surface-to-volume ratio due to diminutive size. Miniaturized Mars surface spacecraft, such as the Tumbleweed Rover, are therefore severely energy-limited in their operation, as the majority of the available energy must be used for maintaining the internal temperature within acceptable limits. As a result, the challenge is creating a thermal management system that meets the mass and power restrictions of the Tumbleweed Rover and protects the electronic systems from Martian thermal conditions.

We examine different design options to actively and passively manage the temperature and protect the interior of a container. This endeavor leads us to a comprehensive investigation of Mars' most extreme conditions, where we meticulously analyze various thermal fluxes and their consequences. Employing advanced simulations, we evaluate the optimization of the thermal system, tactically synchronize heat emissions to maximize efficiency, and rigorously assess the efficacy of insulation. Furthermore, we conduct an examination of the heater's performance, particularly in worst-case scenarios, to ensure robust thermal system.

To determine the most suitable design, we employ computational simulations to scrutinize the thermal properties of the containment system. We fine-tune the operational schedules of electronic and electrical components to maintain an optimal internal temperature and evaluate the role of insulation materials. We show novel ways to conduct a waste heat minimized thermal management by the optimal configuration of the electronic subsystems to be closely related to the operational thermal environment of the respective subsystems. The findings can be used across the board in space missions to minimize energy budgets required for thermal management, especially deep space missions using miniaturized spacecraft.

Keywords: Tumbleweed mission, Mars exploration, rover, swarm, wind-driven, mission architecture

1 Introduction

In our pursuit of Martian exploration and understanding our place in the universe, advanced rovers like NASA's Perseverance play a vital role, despite their limitations in speed and cost. Team Tumbleweed's innovative approach with wind-powered rovers aims make space exploration accessible to everyone; collecting data on Mars' landscape while sharing it with the public.

1.1 Wind-Powered Rovers for Martian Exploration

In our quest for space exploration, with a particular focus on Mars, we aim to shed light on our position in the universe and unlock the secrets of our solar system. Furthermore, we're addressing the intriguing possibility of extraterrestrial life [1].

Currently, we employ advanced Mars rovers, but they have limitations in terms of speed and cost-effectiveness. The mobility of these rovers depends on their model and the terrain they traverse. For instance, NASA's Perseverance rover can travel at a maximum speed of 0.12 kilometers per hour on flat, solid ground [2]. This is a significant improvement over the older Curiosity rover, which had a top speed of only 2 meters per hour (20 m) [3]. The overall cost of the Perseverance rover program includes $2.2 billion for spacecraft development, $243 million for launch services, and an estimated $300 million for operational and scientific analysis during its main 2-year mission [4].

1.2 Team Tumbleweeds Mission

Now, let's turn our attention to Team Tumbleweeds' novel approach: 90 wind-powered rovers. These rovers are equipped with specialized measuring instruments and are ingeniously designed in a cylindrical form. Using a dedicated transfer vehicle, they compactly reach Mars akin to legacy missions, where they unfold into spherical shapes upon arrival. Notably, these rovers begin their unpredictable journey from the North Pole of Mars. Some of them will eventually roll down to rest somewhere along the Martian equator due to a triggered stopping mechanism, while others may find themselves wherever their journey ends. These light-weight rovers are unique in that they use sails to harness Martian winds for efficient propulsion, as depicted in the 3rd prototype in figure 1 and the Mission Concept in figure 2. Throughout this remarkable journey, they traverse random paths while continuously collecting valuable data for a year, ultimately focusing on data collection from the northern hemisphere of Mars.

Figure 1: Team Tumbleweed Rover Prototype Version 3 at the Mars-simulation "AMADEE-20" in the Negev desert in Israel

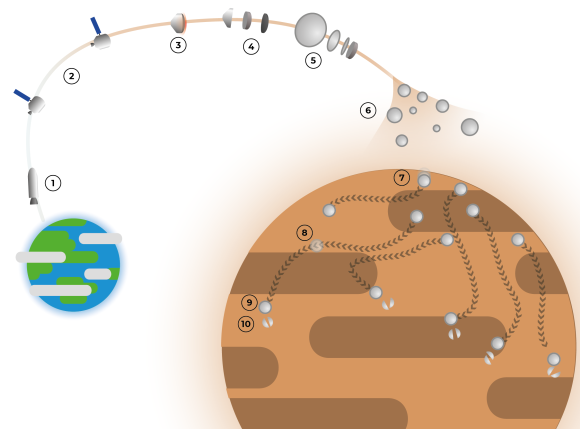

Figure 2: Tumbleweed Mission Concept: 1. Launch, 2. Transfer, 3. Entry & Descent, 4. Separation, 5. Deployment, 6. Unfolding, 7. Landing, 8. Mobile Operations, 9. Stationary Operations, 10. Decommissioning [5]

As part of our overarching mission, we aim to make deep space exploration accessible to a wider audience by sharing the data collected by these wind-powered rovers. This collaborative approach enables space enthusiasts and researchers to actively participate in our collective effort to uncover the secrets of Mars and expand our knowledge of the broader universe.

1.3 Pods: Protecting Critical Systems from Harsh Martian Conditions

In the pursuit of successful Martian exploration, the electrical system is housed within two protective enclosures referred to as "pods." These pods serve as essential shields, safeguarding crucial components responsible for data collection, communication with Earth, and energy management from the formidable Martian environment. This environment comprises challenges such as abrasive dust, harmful radiation, and extreme temperature fluctuations. To ensure the reliability and functionality of the electrical system, it is imperative to maintain a stable temperature range between 0°C and 30°C within the pods. This is especially challenging given that the outside temperature fluctuates between 20° C and -153° C [6]. Achieving this thermal equilibrium relies on a sophisticated thermal management system, comprising various components that actively regulate temperature (heaters, variable conductance heat pipes) or passively insulate and reuse waste heat.

1.4 Thermal Challenges and Criteria for Pods

In the design and construction of these pods, several critical criteria must be met to ensure their effectiveness.

Weight Budget: One paramount consideration is the weight budget. Strict weight limitations are imposed on the pods due to their impact on the rover's mobility. A lighter rover benefits from the Martian winds, enabling it to cover greater distances—an integral aspect of the Team Tumbleweed mission. Presently, the weight limit for the thermal management system stands at a stringent 0.5 kg.

Energy Budget: Another crucial criterion is the energy budget. Given that the rover relies on previously charged batteries and solar-generated energy, stringent restrictions are placed on the energy consumption of the thermal system. To comply with this limitation, the instantaneous power consumption shall not exceed 5 watts (W).

1.5 Objectives of the Study

The primary objective of this study is to verify the effectiveness of chosen thermal measures using simulation where the temperature inside the pod is tracked. This is accomplished through the development of a thermodynamic model, utilizing data interpolations sourced from the Martian Climate Database for the year 2032. The outcome of this endeavor is a comprehensive map of a Martian hemisphere, identifying regions with varying temperature profiles, including cold and hot spots. Subsequently, strategic thermal measures such as insulation, active heating, and the reuse of emitted energy from electronic components are incorporated into the model. New simulations are conducted to evaluate the impact of these measures. Based on the insights derived from these simulations, this paper will provide recommendations for the ideal thermal measures to be implemented in constructing a pod prototype that aligns with the specific requirements of the Team Tumbleweed mission.

2 Thermal Measures

There are many ways to influence the temperature inside a housing. In the pursuit of suitable thermal measures, an exhaustive summary and categorization of findings have been accomplished. However, most of these possible thermal measures do not comply with the strict mass and energy budget of Team Tumbleweed's mission. Due to Mars' extreme temperature fluctuations (from 20° C to -153° C [6]), active heating and cooling methods are crucial for operational stability and precise pod temperature control. Furthermore, the utilization of insulation presents an energy-free solution.

2.1 Thermodynamic Strategies for Maintaining Optimal Conditions

Within the context of optimizing Martian rover performance, diverse thermal strategies are explored. These encompass establishing effective pathways for internal electronics cooling, efficient heat dissipation into the Martian environment, and multifaceted internal temperature regulation methods. These strategies involve technologies like heat pipes, thermal interface materials, radiators, dynamic control systems, and active heating solutions to maintain critical electronic components within specified temperature ranges amid the demanding Martian environment.

Conduction Path for Electronics Cooling

In our pursuit of ensuring the operational efficiency of Martian rovers, it becomes imperative to establish a robust conduction pathway for the cooling of internal electronics. This objective can be accomplished through the judicious integration of heat pipes [7], thermal interface materials [8], fluid loops [9], and oscillating heat pipes [10]. These thermal conduits facilitate the dissipation of excess heat generated within the system, ensuring that critical electronic components operate within specified temperature ranges.

Efficient Heat Dissipation into the Environment

To manage excess heat on Mars-bound systems, efficient heat dissipation via radiators and specialized coatings is crucial [10] [11]. Radiators transfer heat to space through radiation, and additional plates can be used to enhance this process for components prone to overheating [11].

The Mars Thermal Environment and Radiator Characterization (MTERC) Experiment evaluated various radiator types in a simulated Martian environment [12]. It included flat-plate and deployable radiators, which performed well, while heat pipe and loop heat pipe radiators were less effective. Surprisingly, the experiment also revealed that the night sky temperature on Mars was colder than expected, impacting radiator design considerations for future Mars missions [12].

Regulation of Internal Temperature

Maintaining the desired internal temperature within the pods is a multifaceted endeavor, with several strategies at our disposal:

- **Thermal Insulations:** Leveraging the insulating properties of materials such as foams, fibrous insulations , multi-layer insulation (MLI), and aerogel enables the preservation of internal temperature without additional energy consumption. Lightweight options like foams and aerogel exhibit favorable environmental resistance characteristics and can be further shielded as needed [13] [14] [15].
- **Dynamic Control of Cooling Systems:** Employing dynamic control mechanisms, such as heat switches or thermostats, allows for the intelligent control of the thermal system based on prevailing environmental conditions. This approach optimizes energy usage while ensuring the maintenance of the desired temperature range [10] [11].
- **Active Heating for Low-Temperature Conditions:** To counter excessively low temperatures, an active heating component is indispensable within the thermal system. Two viable options in this regard are heaters and infrared (IR) lamps [16] [17].
- **Efficient Heat Dissipation for High-Temperature Conditions:** In the event of elevated temperatures, efficient heat dissipation mechanisms must be in place. Variable conductance heat pipes, temperature-controllable oscillating heat pipes, pressure-controlled heat pipes, or the use of louvers can all be considered for effective heat dissipation [18] [19] [20].

2.2 Evaluation of Suitability for Simulation of Potential Thermal Solutions for Team Tumbleweed

In order to establish the foundational requirements and challenges encountered by the thermal environment, a simulation of the Pod Thermal System is conducted.

In light of the stringent weight and energy budget constraints, the selection of thermal solutions must prioritize those that are essential and energy-efficient. Given the wide temperature fluctuations on Mars, ranging from 20° C to -153° C [6], an active heating device, such as a heater or an IR lamp, is deemed critical to maintaining operational integrity. Furthermore, an active cooling component is essential for precise temperature control within the pods, ensuring scientific mission success. However, these components can only present the last resort of controlling the temperature other energy and mass efficient measures need to be taken into consideration. A passive and lightweight measure, such as insulation, which can be applied externally to the pods without obstructing vital components, warrants consideration. It is one straightforward and feasible static measure that can be readily integrated into the simulation. Additionally, optimizing times of operation of the electronic components to effectively utilize heat emissions presents a viable option for real mission implementation, requiring neither additional mass nor energy. Notably, other measures, characterized by their dynamic nature or non-compliance with the stringent mass and energy budget, have been omitted from the simulation.

As mentioned, the thermal difference between the simulated temperature and the accepted range of working conditions needs to be compensated by the heating and cooling system. Using the simulation preliminary estimations and requirements for this system can be set. Furthermore, it becomes possible to establish the criteria for additional energy efficient dynamic measures for further investigations or empirical experiments.

3 Methodology

A Python-based thermodynamic simulation was developed to assess temperature variations across diverse Martian locations over the course of 2032 (year of Team Tumbleweed full scale mission) with the aim of identifying thermal extremes and estimating the requisite thermal countermeasures.

3.1 Python as the simulation language

The selection of Python as the programming language was motivated by its compatibility with data retrieval from the Martian Climate Database (MCD) and its adaptability for constructing a flexible thermodynamic model. Python also facilitates the integration of thermal mitigation strategies, such as insulation, into the model.

3.2 Assumptions

In this modeling endeavor, certain assumptions were made, including treating the content within the pods as a solid block with a fixed mass and specific heat capacity. The total mass budget for this system was established at 2.5 kilograms, fully utilized. Materials within the electronics encompass plastics, raw materials, chemicals, and various metals like lithium, tin, silver, gold, nickel, and aluminum, each with distinct heat capacities. A composite heat capacity of 1000 J/(kgK) was assumed for the materials mix. This simulation pertains to a stationary rover, while the actual ones are mobile. Scenarios involving the rover moving in conjunction with temperature gradients were excluded, as modeling both the rover and its thermodynamic system concurrently would make matters much more complex. Cases where a rover moves along the temperature gradient are yet to be examined.

3.3 *Thermodynamic Model*

The resulting thermodynamic model incorporates factors such as solar radiation and its reflection from the Martian surface (albedo), Martian black body radiation, heat transfer mechanisms driven by both natural and forced convection (attributable to Martian winds), and the black body radiation emitted by the pods, see 3. Additionally, a daily periodic cycle of the electrical system was introduced, with heat emissions corresponding to the active periods of individual components.

3.4 *Environmental Data Base*

To furnish the simulation with essential atmospheric data, parameters were sourced from the Martian Climate Database, integrated seamlessly into the Python code executing the simulation. Data points, acquired at 15-minute intervals, were practically chosen to inform the model accurately while keeping the simulation time acceptably low. The parameters encompassed Solar zenith angle, Surface temperature, Surface pressure, Incident solar flux, Reflected solar flux, Thermal IR flux, Atmospheric density, Azimuth angle, dynamic viscosity, and an absolute wind speed calculation, as per the MCD documentation [21][22].

3.5 *Conducted Simulations*

The study investigates extreme thermal conditions on Mars by analyzing temperature data from the year 2032 using the Martian Climate Database (MCD). The focus is on identifying the hottest and coldest locations, along with their corresponding months and days, within latitudes +90 to -50 degrees.

The simulation of the Tumbleweed thermal system without any thermal measures involves using the MCD data, setting up a thermodynamic model and assess the impact of heat sources during the hottest and coldest month.

To optimize thermal control, the study proposes synchronizing heat emissions from the electrical system with the Martian day and night cycle during the coldest month (October) at the coldest location on Mars. The goal is to find the optimal synchronization point of the electrical cycle and the day and night cycle that maximizes the minimum temperature inside the pod.

The study also explores the impact of an insulation, by varying insulation thickness while keeping other parameters constant. For the simulation aerogel was chosen. This analysis aims to understand how the implementation of an insulation and changes in insulation thickness affect the pod's temperature conditions.

Temperature field on Mars

To investigate the most extreme thermal conditions on Mars, a comprehensive analysis is conducted. Extrapolated temperature data for the year 2032 is extracted from the Martian Climate Database (MCD), and the most extreme thermal conditions are tracked and plotted on two heatmaps to visualize temperature variations across the Martian landscape.

To comprehensively study Mars' extreme temperature conditions, we needed to find the hottest and coldest spots on the planet and figure out when these extremes occur. Our analysis mainly concentrated on regions with latitudes between +90 and -50 degrees, as the mission focuses on the northern hemisphere.

Simulation of Tumbleweeed Thermal System without Thermal Measures

Using the environment data from the MCD, a thermodynamic model is set up and simulated over the course of the previously determined hottest and coldest months. The average impact of every heat source is determined to further assess appropriate countermeasures.

Reuse of Waste Heat

To optimize thermal control from the outset, the first proposed measure is to synchronize heat emissions from the electrical system with the Martian day and night cycle. For this, a preliminary cycle was defined, that specifies in which order and at what relative times the electrical components operate. Given the critical nature of addressing the challenges posed by extreme cold temperatures, a rigorous assessment is conducted during the coldest month, which is October, at the most frigid location on Mars.

During this assessment, the start of the electric cycle is systematically shifted at 15-minute intervals, and the resulting minimum and maximum temperatures are closely monitored. The objective is to identify the shift that would yield the highest minimum temperature, thus improving the thermal conditions within the pod.

Insulation

For the simulations, the properties of aerogel are given, see reference [23]. Aerogel is renowned for its exceptional insulating properties, making it an attractive candidate for analysis. In the simulations, the thickness of the insulation material is varied while keeping the other parameters constant, allowing for the evaluation of how the

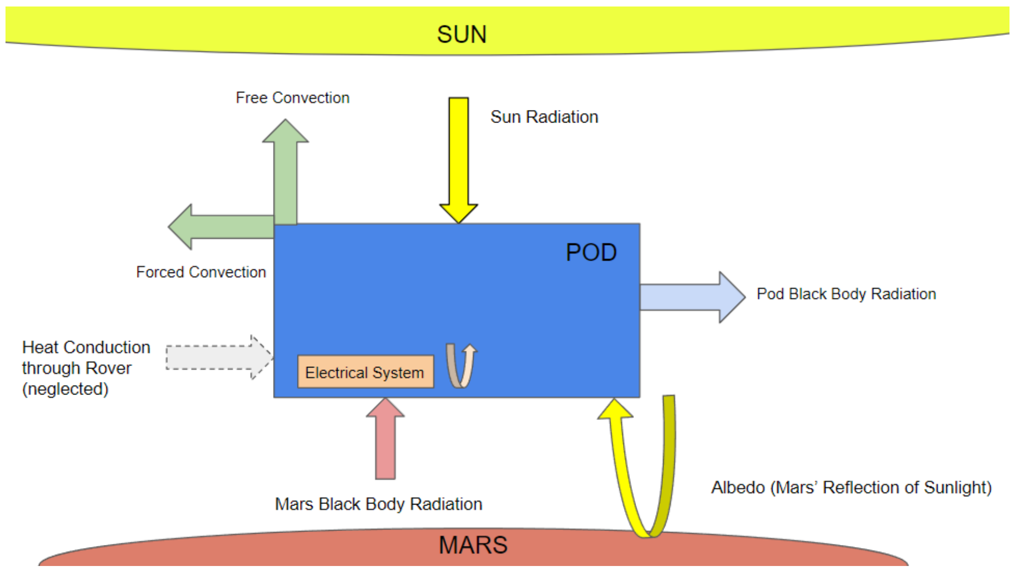

Figure 3: Sketch of Team Tumbleweeds thermodynamic model

implementation of insulation as well as changes in insulation thickness affect the temperature conditions within the pod. The conditions for the coldest day (October 1st) are used as the environment for this study.

Heater

As a final contingency, we recognize the vital role of the heater in ensuring the pod remains within the prescribed temperature range of 0 to 30 degrees Celsius, crucial for safeguarding the integrity of the onboard electronics. At this juncture, simulation does not incorporate any thermal control system yet. Instead, we are only numerically calculating the minimum power required from the heater to sustain the desired temperature range. The conditions for the coldest day (October 1st) are used as the environment for this study.

4 Results

The findings suggest that Mars experiences extreme temperature variations, with the coldest day in 2032 relevant to the mission occurring on October 1st at coordinates -120 degrees longitude and -10 degrees latitude, dropping to a frigid -127 degrees Celsius, while the hottest day is on January 4th at coordinates 20 degrees longitude and -30 degrees latitude, reaching a peak of +29 degrees Celsius. Given the prevalence of colder temperatures, the need for heating measures is prominent.

The simulation of a Tumbleweed thermal system without thermal measures displays the average impact of every heat source, emphasizing the significance of waste heat and forced convection. Solar irradiance plays a more substantial role in the hot case.

In contrast, simulations with thermal measures, such as shifting the synchronization point or implementing insulation, demonstrate the importance of precise synchronization strategies and the effectiveness of insulation in temperature control. The heater's role is highlighted in maintaining the electronics' temperature within the desired range.

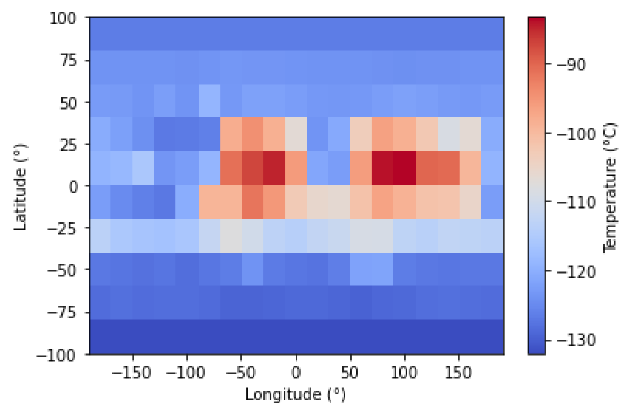

Figure 4: Minimum temperature reached at different grid points over the year 2032

4.1 *Temperature field on Mars*

Our findings reveal that the coldest day on Mars in the year 2032 that is relevant for the mission as the lower part of the southern hemisphere is disregarded, occurs on October 1st, situated at coordinates -120 degrees longitude and -10 degrees latitude, with temperatures plummeting to a frigid 127 degrees Celsius, see figure 4 and 5. Conversely, the hottest day manifests on January 4th, positioned at coordinates 20 degrees longitude and -30 degrees latitude, where temperatures soar to a peak of +29 degrees Celsius, see figure 6. As more extreme cold temperatures than hot temperatures are reached on Mars, the case of needing to keep the electronics warm from the outside is more dominant. The first of October at -120 degrees longitude and -10 degrees latitude serves as the foundation for our subsequent calculations and considerations.

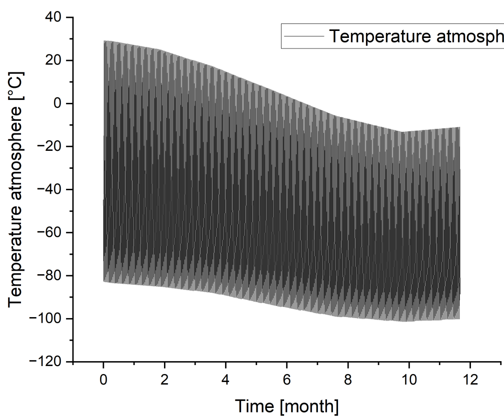

Figure 5: Temperature graph at -10 ° latitude, -120 ° longitude over the year 2032

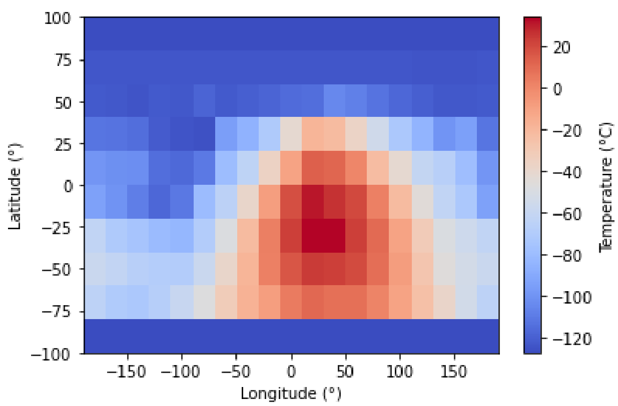

Figure 6: Minimum temperature reached at different grid points over the year 2032

4.2 *Simulation of Tumbleweed System without Thermal Measures*

The thermodynamic model in the Martian environment was simulated. The exemplary result of the temperature inside the pod is shown in figure 7. It becomes clear that thermal measures are desperately needed, as the temperature inside the pod is just above the ambient temperature reaching -70 ° Celsius.

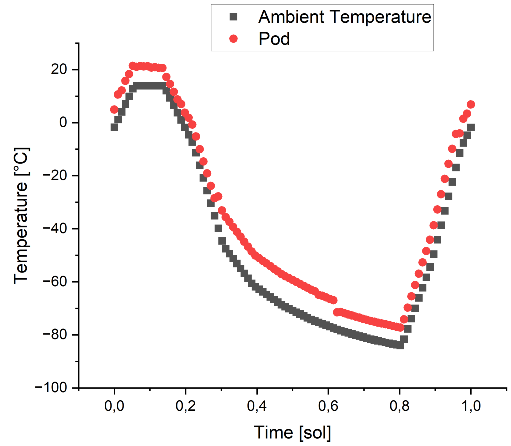

Figure 7: Temperature inside the pod without additional thermal measures on January 1st 2032 at 0 ° latitude, 0 ° longitude

The heat sources are exemplary plotted over time, see 8.

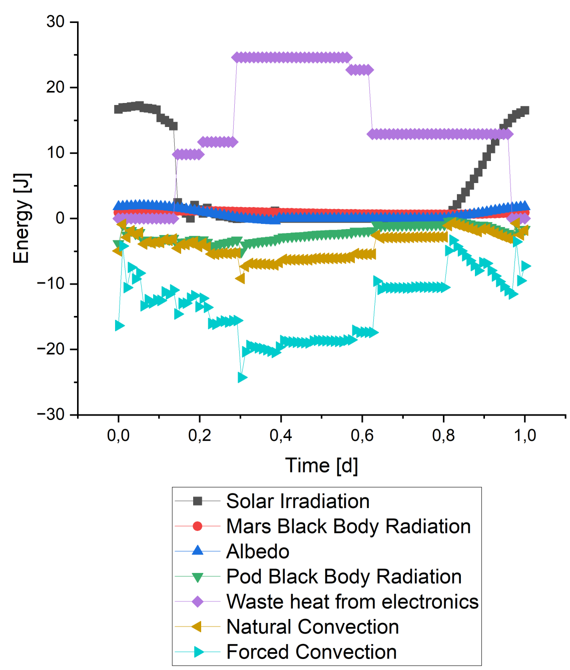

Figure 8: Heat fluxes on January 1st 2032 at 0 ° latitude and 0 ° longitude

Figure 9 presents an assessment of the average energy impact (measured in Watts) within this system. We compare the influence of energy flux during the two months characterized by the most extreme temperatures identified earlier in our study.

Waste heat management assumes significant importance in maintaining optimal electronic functionality. As anticipated, solar irradiance exhibits greater prominence in the context of elevated temperatures. Conversely, albedo and Mars Black body radiation exert relatively minor influences in both scenarios. The thermal emissions from the Pod's Black Body Radiation source exhibit a similar, moderate impact across both cases.

Notably, convection, particularly in the form of forced convection, assumes a pivotal role in this system. Forced convection, in particular, plays a significant role in heat dissipation, a fact underscored, especially in the context of higher temperature conditions.

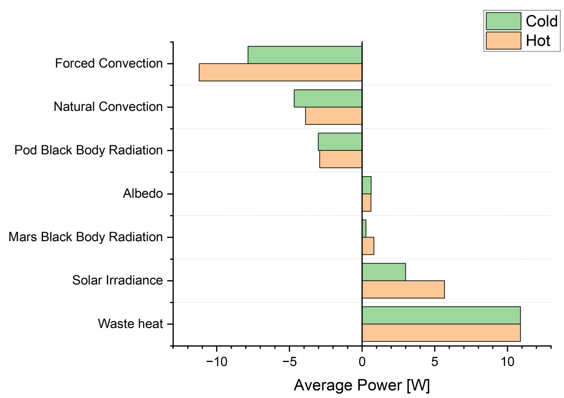

Figure 9: Average power of heat fluxes during October at -10 ° latitude and -120 ° longitude (cold) and January at -30 ° latitude and 20 ° longitude (hot)

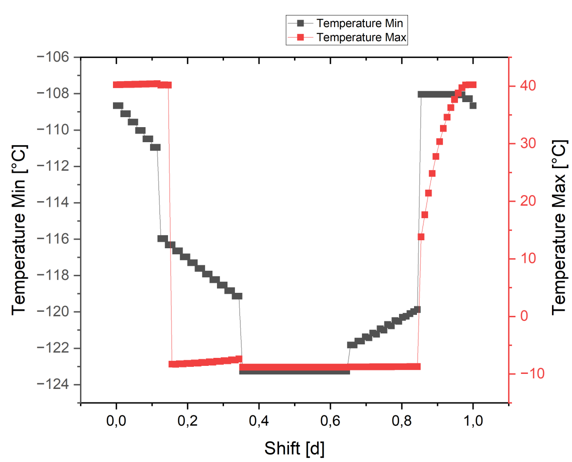

Figure 10: Impact of shifting the electrical cycle by different day fractions on the minimum and maximum temperature reached inside the pod during October 2032 at -10 ° latitude and -120 ° longitude

4.3 *Simulation of Tumbleweed System with Thermal Measures*

Reuse of Waste Heat

Our analysis unveil that in the cold case a shift of 0.9 days from the standard synchronization point produces minimal temperatures of -108 degrees Celsius and a maximum temperature of 33 degrees Celsius, see 10. In contrast, a less ideal synchronization, such as a 0.5 days shift, would lead to temperatures plummeting to -123 degrees Celsius, emphasizing the importance of the selected synchronization strategy.

Insulation

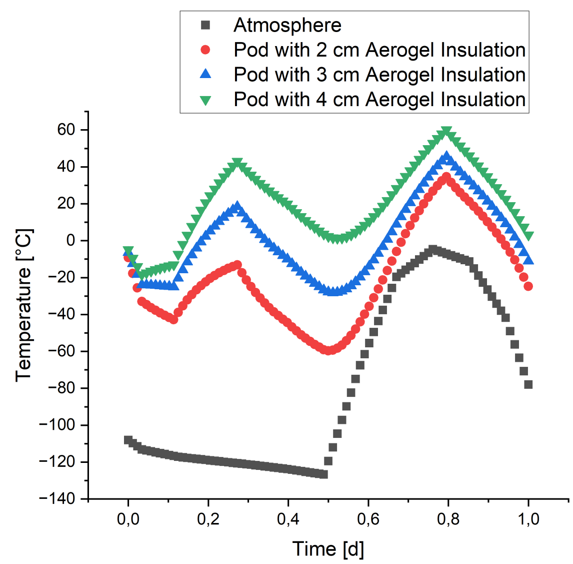

Figure 11: Impact of aerogel insulation on the temperature inside the pod at different thicknesses on October 1st 2032 at -10 ° latitude and -120 ° longitude

In addition to incorporating the optimal time shift of +0.9 days into our simulation, we are also introducing an insulation component. The resulting graphs in Figure 11 exhibit two distinct peaks. The second peak is attributed to the rise in ambient temperature during daylight hours at 0.8 days. The first peak originates from the offset heat flux generated by the electrical components, indicating the effective thermal containment achieved by the insulation within the pod.

However, it's important to note that regardless of external cold temperatures, various insulation types tend to elevate internal temperatures when the external environment warms, necessitating cooling mechanisms. Notably, insulation with thicknesses of 2 cm, 3 cm, and 4 cm adds

0.59 kg, 0.95 kg, and 1.35 kg, respectively, exceeding our 0.5 kg weight budget.

It's pertinent to note that the initial internal temperature of the pod was set to 0 degrees Celsius.

Heater

In this simulation, we are building upon the time-shift and introducing a thermal system that incorporates a combination of three thermal measures. The calculated power output represents the thermal generation from the heater. It's crucial to emphasize that Team Tumbleweed has imposed stringent constraints on peak power consumption for the mission, limiting it to a maximum of 5 Watts.

For this simulation, we have chosen an insulation thickness of 3 cm, based on its promising performance observed in the previous section.

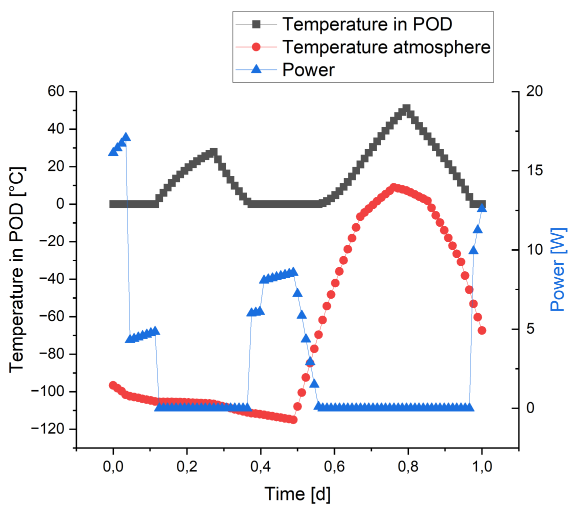

Figure 12: Necessary heating power when utilizing a shift of +0.9 days, 3 cm aerogel insulation on October 1st 2032 at -10 ° latitude and -120 ° longitude

5 Discussion

The analysis of the Martian temperature field revealed limitations in the heatmaps used. Extending research to cover multiple Martian years and exploring broader points of interest could provide a more comprehensive understanding of temperature variations.

In the simulation without thermal measures, forced convection played a significant role, potentially influenced by wind speed gradients, requiring further empirical studies.

For thermal measures, optimizing the electric shift is crucial, considering varying deployment locations and long-distance travel. Lightweight insulation materials have benefits but need careful consideration. Implementing temperature control strategies can reduce peak heater consumption, improving thermal efficiency.

Overall, the combination of thermal measures involving the optimal recycling of waste heat, effective insulation, and temperature compensation through a heater has yielded promising results. These findings will serve as a solid foundation for further refinement and development as we progress in our research.

5.1 Temperature field on Mars

The heatmaps employed in this analysis featured a relatively limited grid of 19 by 10 data points. However, it's important to acknowledge that there may be more intensive temperature variations in regions between +90 and -50 degrees latitude that are not fully captured by this grid. To address this limitation, future research should consider extending the study to cover multiple Martian years, given that a Martian year is longer than an Earth year. This would provide a more comprehensive understanding of temperature variations on Mars.

While the coldest and hottest points on Mars have been identified in this analysis, it's essential to recognize that the coldest points may not necessarily pose the most significant challenges for thermal control. Further investigations could explore a broader collection of points or simulate the movement of pods across the Martian surface, which could reveal additional insights into temperature challenges.

5.2 Simulation of Tumbleweed Thermal System without Thermal Measures

The simulation of the Tumbleweed thermal system without thermal measures has highlighted the critical role of forced convection in dissipating heat. In the hot case, an increase in energy emission was observed, primarily attributed to forced convection. However, it's imperative to acknowledge that this phenomenon may also be influenced by variations in absolute wind speed, necessitating further investigation, particularly under the context of low atmospheric pressure conditions at high Reynolds numbers.

Furthermore, it's firmly established that the implementation of thermal measures is imperative in addressing the thermal challenges posed by the Martian environment.

5.3 Simulation of Tumbleweed Thermal System with Thermal Measures

Optimizing the electric shift in the cold case aims to compensate for temperature drops within latitudes +90 and -50 degrees, but it may need location-specific adjustments during rover travel.

Lightweight insulation was considered, but the heater's energy budget requires about 3 cm of insulation, posing spatial and weight challenges.

Implementing temperature control strategies can reduce peak heater consumption, improving thermal efficiency.

Reuse of Waste Heat

The optimization of the electric shift in the cold case primarily targeted the compensation for the most substantial temperature decline across latitudes ranging from +90 to -50 degrees. Nevertheless, it's crucial to acknowledge that the electric cycle's adaptability may be necessary depending on the precise deployment location of the pod. Moreover, considering that the rover may traverse extensive Martian terrain, continuous adjustments to the electric cycle may be required.

Additionally, it's worth noting that the electric cycle represents a preliminary assumption, and a more in-depth investigation into the electrical concept is warranted. Deviations from a specific sequential order in which the components operate may emerge and should be thoroughly explored.

Insulation

The chosen insulation material, while lightweight, presents a challenge concerning the energy budget for the heater. Maintaining an insulation thickness of approximately 3 cm is essential, taking into account spatial and weight restrictions. Therefore, the trade-off between insulation thickness and weight is a critical factor that should be carefully evaluated in the thermal control system design.

It's worth noting that despite the current insulation choice, there exist more efficient and lightweight insulation materials (detailed in Section 2). However, their integration into our simulations remains pending due to the unavailability of material specifications or the complexity associated with simulating their insulation properties.

Heater

The heating power consistently exceeds the 5 Watts threshold on multiple occasions. Nevertheless, with the implementation of intelligent heating control strategies, these peak power requirements can be mitigated. The optimization of this control mechanism represents a focal point for future investigations. For instance, one approach might involve setting a target temperature of approximately 15°C with permissible temperature deviations of up to 15°C. Alternatively, an intelligent strategy could entail proactively raising the temperature to 25°C in anticipation of the colder nighttime conditions. These avenues warrant further study and refinement in our research endeavors.

6 Outlook

The simulation results demonstrate a realistic portrayal of our thermal management strategies. Intelligent thermal control, as briefly mentioned in the Outlook section, represents a crucial avenue for further exploration. Additionally, it's imperative to address the unique challenges posed by the North Pole region on Mars. Here, we encounter consistently cold temperatures, necessitating careful consideration within the context of our overall energy budget, which is yet to be established.

Furthermore, the electronic system employed in our mission requires in-depth discussion. Exploring the possibility of implementing additional communication procedures, conducting more measurements, generating waste heat on demand could potentially obviate the need for a dedicated heater. However, further research is required to ascertain the feasibility of these strategies.

While cooling methods were not the primary focus of this paper, they undoubtedly merit attention. When utilizing insulation, there is a potential for surpassing the 30-degree Celsius threshold. Viable cooling options include variable conductance heat pipes and a heat switch, which should be explored in subsequent studies.

To further enhance our understanding and refine our approach, our future endeavors involve acquiring additional data from the Martian Climate Database (MCD), particularly pertaining to wind gradients over a span of multiple years, as forced convection plays a significant role.

We plan to integrate this dataset into our simulations, extending our analyses to include the movement of the Team Tumbleweed Rover across the Martian terrain. Additionally, we recognize the need for more sophisticated simulation tools, such as COMSOL, which can accommodate intricate insulation properties and facilitate 3D modeling of thermal control within the pod. This is especially crucial for comprehending the distribution of temperatures caused by heat diffusion.

Furthermore, as we progress, we acknowledge the significance of the arrangement of electronic components within the pod. Notably, not all electrical elements adhere to the strict operational temperature range of 0 to 30 degrees Celsius. Hence, strategic placement of these sensitive components within the pod will be a critical consideration.

Once our simulations are meticulously conducted and we have a preliminary pod design in place, we will proceed with the physical construction of the pod. This stage will be vital for real-world testing of our thermal management system under Martian conditions.

Beyond thermal management, we recognize the need to investigate other aspects of the pod's functionality. This includes developing measures to mitigate the impact of Martian dust and radiation, ensuring structural integrity, equalizing pressure differentials with the environment, establishing secure mounting points for the pod's contents, and implementing vibration dampening mechanisms. Each of these facets contributes to the overall success of our mission, and their thorough exploration is integral to our research.

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