Design of Thermal Systems for Cryocooled Sensors in Space Rovers with Feedback Loop

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ABSTRACT

The lifespan, performance and efficiency of planetary rovers mainly depends on how efficiently the thermal management system works. In order to maintain the desired temperature level of the sensors, a cooling system using a cryocooler may be required. This paper deals with incorporating a cryocooler with a feedback control system for ensuring effective cooling. Of the different types of cryocoolers, we have chosen a Stirling cryocooler for this study. The feasibility of the proposed control system is simulated using the SIMSCAPE(MATLAB) software package, and the complete model of the Stirling cryocooler is designed and optimized using SAGE v.11 software.

In SIMSCAPE, a sine wave generator is used to model the variation in the temperature of the sensors during their operation; heat gain to the sensors via conduction and convection is also modeled. The whole system is controlled using a feedback loop and a relay that takes the corresponding reference temperature of the sensors as the control parameter.

INTRODUCTION

Space exploration has vastly increased over the last few decades. In the initial days, space exploration was heavily funded by military defense-related projects, but the trend subsided quickly, and people began to understand the value behind space exploration in spite of the overwhelming cost of conducting it. In this journey, due to the cost and risk of conducting exploration with humans, there has been a growing focus on using rovers to conduct space exploration. Planetary rovers are mostly remote-controlled, small-scale mobile devices that are able to traverse the harsh surfaces of various planets such as Mars. These rovers are designed to collect various data that are needed for the analysis of the extraterrestrial planet. As it is expensive to launch rovers to outer space, only a limited number have been launched, and they are expected to operate for a long period of time without any human maintenance.

One of the difficulties that rovers face is the extreme temperature variations on different terrestrial planets. For example, on the Martian surface, the atmospheric temperature varies from 0 to -100°C within the span of a single day. Since the rovers depend on delicate electronic devices, it is important to maintain their operating temperature within narrow margins, even if the atmospheric temperature is not at all favorable.

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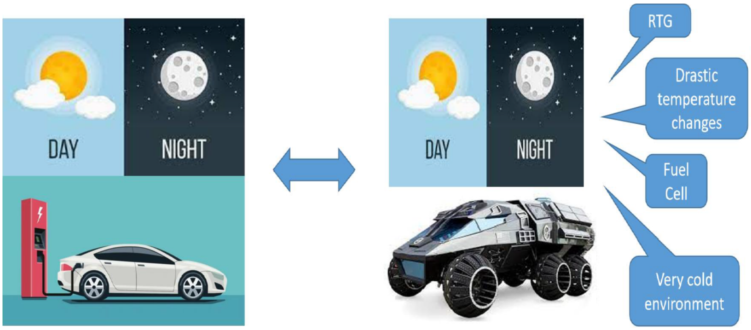

Figure 1. Comparison Between Rover And Electric Vehicle

There are many different sensors that can be included inside a rover, such as temperature sensors, visible and infrared viewing sensors, positional sensors, wind speed sensors, etc. Of these, infrared sensors often require cryogenic temperatures to achieve low-noise operation. In this work, we examine means of designing a temperature control system using modeling software, in particular the Simscape software package of Matlab. Because we include a cryocooler in the system design, we include the design of the required cryocooler itself using Sage software.

To provide representative external environmental conditions, we have selected a Mars-like environment for the variation of the external atmospheric temperature. The thermal management of the whole rover is also taken into account. As the IR sensor is cooled down to a very low temperature, it will experience a variety of heat loads not only from the external Martian atmosphere, but also from the detailed internal thermal makeup of the rover.

The inspiration behind this work is the time and effort put forward by thermal engineers all over the world in the space application sector. Their work is concentrated on achieving the thermal requirements needed by the various crucial parts of the rover including the electronics inside the rover's cabin. An interesting model is the relation or similarity between electric vehicles and rovers as noted in Fig. 1.

Most of the detailed design that is focused on the inside of the rover is confidential and is not available to the public. Hence, the goal of this project is to provide a generic example of how to tackle a thermal control problem with available simulation software. As noted in Fig. 2, the workings of electric vehicles and rovers are very similar, the main difference being the working environment and the energy sources used. Other differences include items like the materials used for constructing a rover versus an electric vehicle.

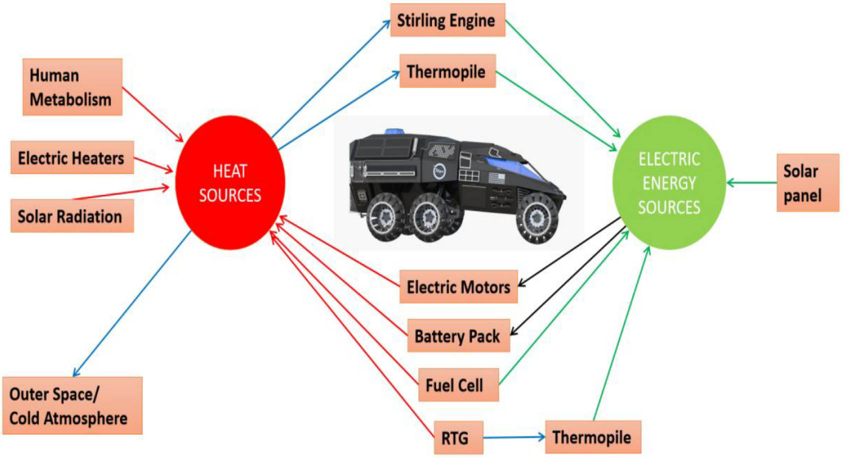

Figure 2. Overall Layout Of Various Energy Interactions

MODELLING OF THE COMPLETE SYSTEM

Design of Main Energy Source

In our thermal management system simulation, different sub elements are considered for study. These include different energy sources such as RTGs, battery pack, fuel cell, etc. A common energy source for a planetary rover that is reliable and efficient is a Radioisotope Thermoelectric Generator (RTG). An RTG uses the heat that is released by the nuclear decay of Plutonium 238 to power a number of thermocouples that generate the required amount of electric energy. A typical rover will consume around 125W of power on average, hence the amount of Pu-238 that will be required can be estimated from the following equations:

$$\mathrm{N(t)} = \mathrm{N_0}\left(\frac{1}{2}\right)^{\frac{\mathrm{t}}{\mathrm{t_{HL}}}} \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{dt}}\mathrm{N(t)} = -\frac{\left(\frac{1}{2}\right)^{\frac{t}{t_{HL}}}.ln(2)}{t_{HL}} \tag{2}$$

As a rough estimate, we can take the power requirement (125 W), and take a representative efficiency of 6.2% for a thermoelectric generator; this gives a needed energy input of ~2016 W. Using the half-life equation (Eq. 1), we can find an estimated amount of Pu-238 that is required to generate this much energy. From the calculation, the amount of Pu-238 required is 3.75 kg, which can be held by eight GPHS (General Purpose Heat Source) modules.

Modelling of the Proposed System in Simscape

The first step in modelling the system in Simscape was to address the various heat transfers occurring inside the rover. The external Martian environment is a prime consideration, particularly the variation in the atmospheric temperature. The atmospheric temperature of Mars varies between 0 and -100°C during the span of a day, and it gets even colder in the polar regions of Mars. The modes of heat transfer chosen were conduction and convection, while radiation was not taken into account for the time being. The entire thermal system of the rover was addressed to provide an estimate of the heat transfer that may occur while trying to maintain the IR sensor thermal conditions. Since the sophisticated electronics onboard the rover need to be maintained at around 20°C, the electronics thermal management system has to be equipped with a proper control system also, as it is assumed to regulate the flow of the primary thermal-control working fluid. Figure 3 illustrates the proposed model of the thermal management system. As shown in the figure, the whole system can be divided

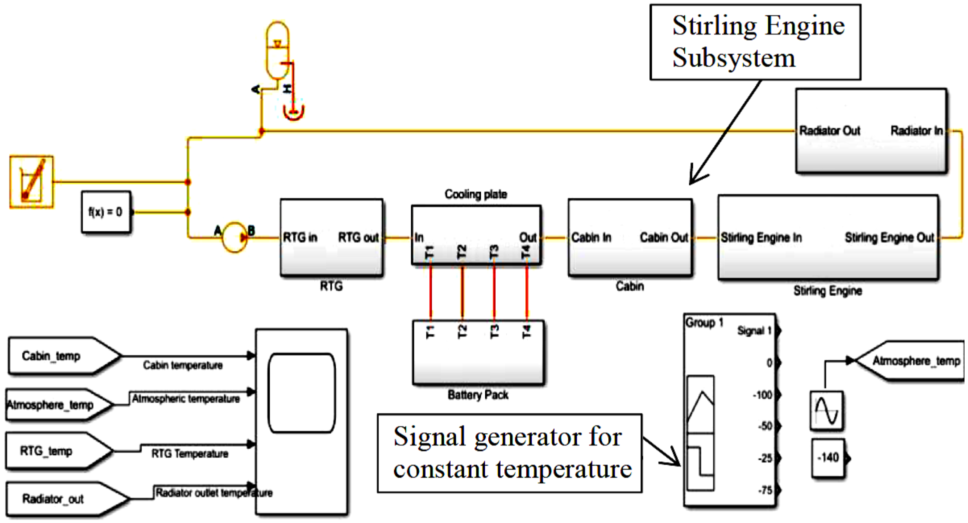

Figure 3. Overall system layout

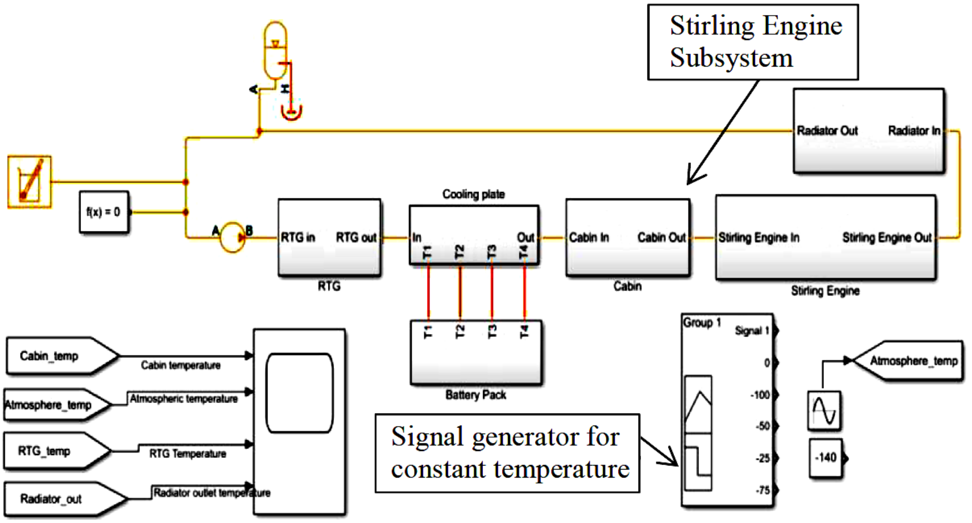

Figure 4. System layout of Cabin

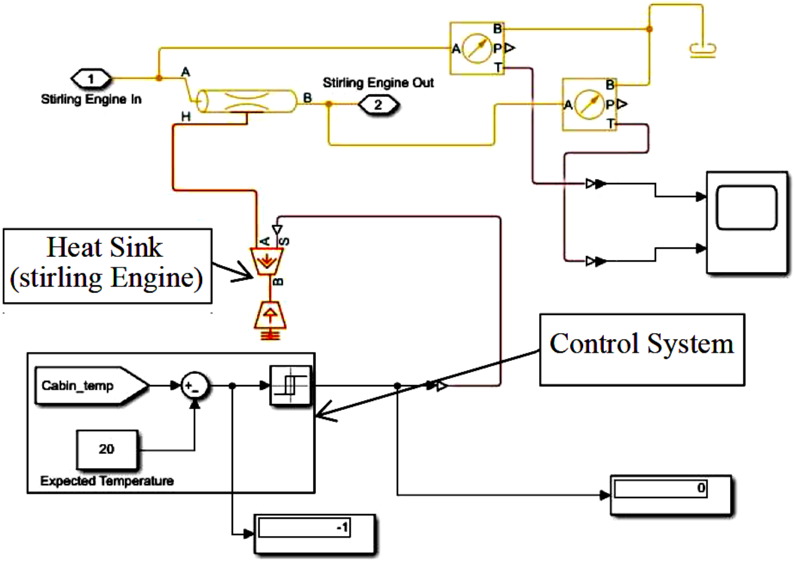

Figure 5. Detailed layout of Stirling engine subsystem

into four subsystems: RTGs, Cabin space, Stirling engine, and Radiator. Each of these subsystems works in unity to form the thermal management system required to keep the thermal conditions of rover in check. Detailed views of each of the subsystems are shown in Figure 4 and 5.

The whole system is able to successfully maintain the required thermal conditions inside the rover. The reference temperature of the electronics is used for controlling the temperature regulation, and this is achieved using a relay block in Simscape. Based on the preliminary analysis, the system is able to work even under very low temperature down to -135°C. Tables 1 and 2 show the specifications of the designed parts of the system. These values are given as inputs for running the Simscape simulation.

The whole system now consists of two different sources of heat energy and one additional heat sink system besides the radiator to reject the excess heat. When the atmospheric temperature is

Table 1. Specifications of Radiator

Specifications				
Radiator	Pipe Length	20.9578 m	Thermal Conductivity	401 W/mK
	Cross sectional Area	1.963 x 10-3 m^2	Mass	58.9934 Kg
	Hydraulic diameter	0.05 m	Specific Heat	0.385 J/kgK
	Area of Heat Transfer	3.292 m^2	Convective heat transfer coefficient	5 W/m^2K
	Thickness	0.002 m		

Table 2. Specifications of RTG Heat distribution plate

Specifications		
RTG - Heat distribution Plate	Plate Thickness	0.02m
	Mass	12.664 kg
	Density (Cu)	8960 kg/m^3
	Specific Heat (Cu)	389 J/kgK
	Pipe Length	230 cm
	Thermal Conductivity (Cu)	394 W/mK
	Heat Generation Rate	2000 W

around 0°C, the constant heat source (RTG) delivers around 2000W and heats up the rover cabin. Part of this heat will be rejected by the radiator, which is always in contact with the thermal loop. When the cabin temperature is more than the expected temperature, the additional heat sink that we added earlier is activated using a controlled relay system. The heat sink here is the Stirling engine. The engine will now use the heat from the loop in order to generate useful power instead of the heat being simply rejected to the atmosphere. Now our thermal management system is reaching closer to the ideal situation in which all waste heat is utilized.

As shown in Figure 6, the new model is able to maintain the cabin temperature at 20°C when the atmospheric temperature is at 0°C. The radiator outlet temperature and the temperature of the RTG heat distribution plate is also shown in the graph.

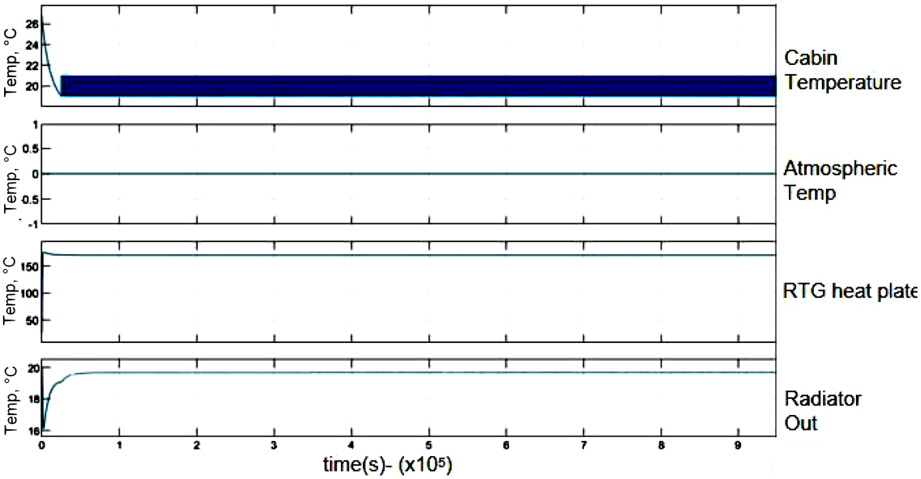

Figure 6. Temperature of various sections of the system at 0<”C atmospheric

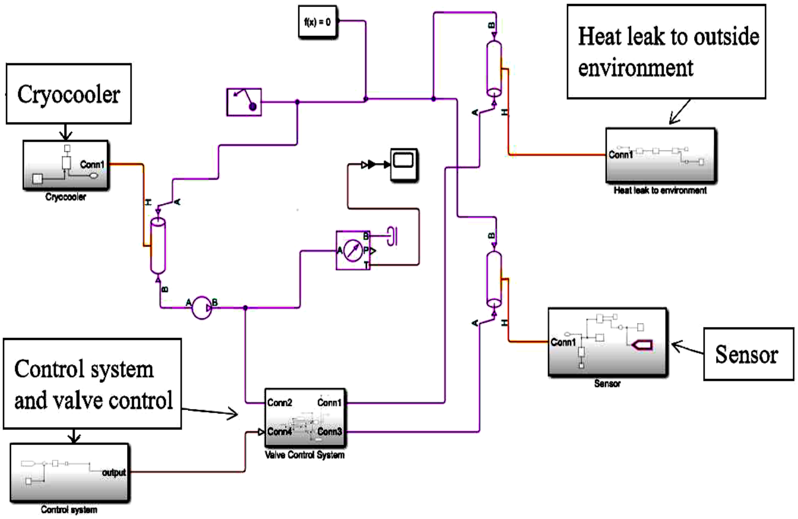

Figure 7. Detailed layout of sensor and Helium loop

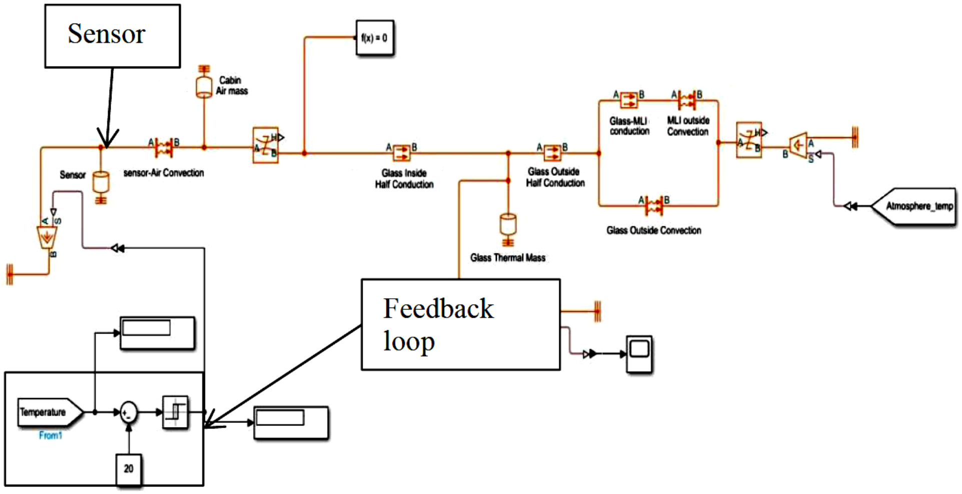

Figure 8. Detailed layout of sensor

Now that we have an estimate of how much heat is being produced and maintained inside the rover, the sensor part can be designed. The infrared sensor is fixed inside a glass shield and partly covered by MLI (Multi Layer Insulation) on the bottom part of the glass dome. The heat transfer from this to the surroundings is considered similar to electrical analogy of heat transfer.

The designed model of the sensor in Simscape is illustrated in Figure 7 and 8. Figures 9 to 11 further describe the output of the simulation models.

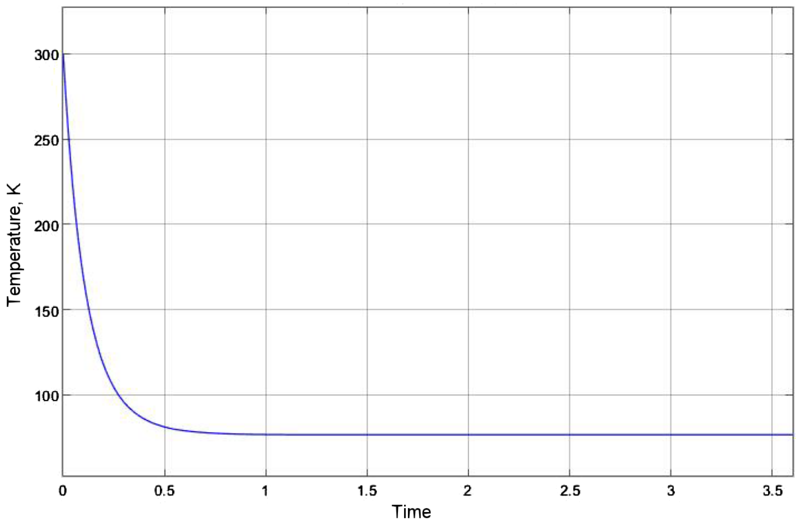

Figure 9. Temperature of sensor during cryocooler cooldown.

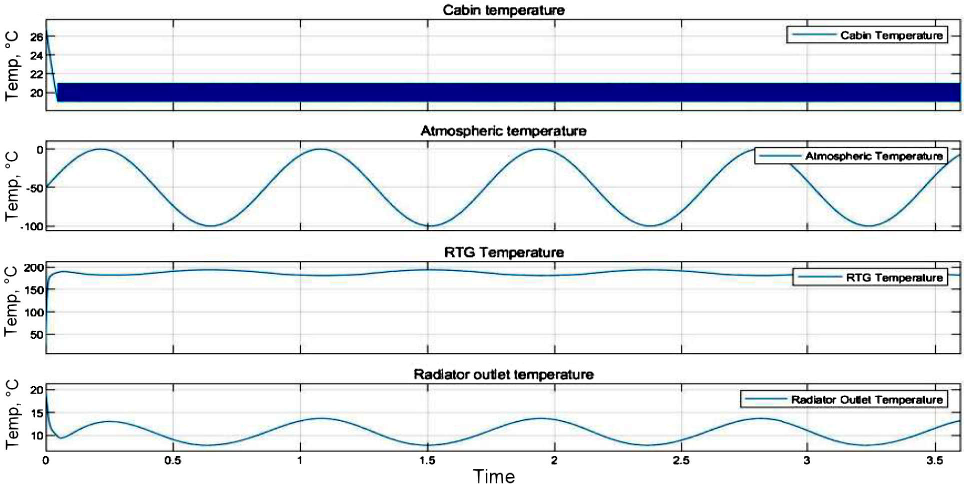

Figure 10. Sinusoidal variation in the atmospheric temperature and the corresponding cabin temperature.

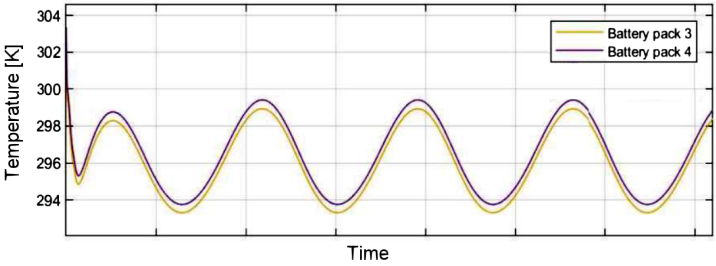

Figure 11. Temperature variation of the battery pack with sinusoidal variation in atmospheric temperature

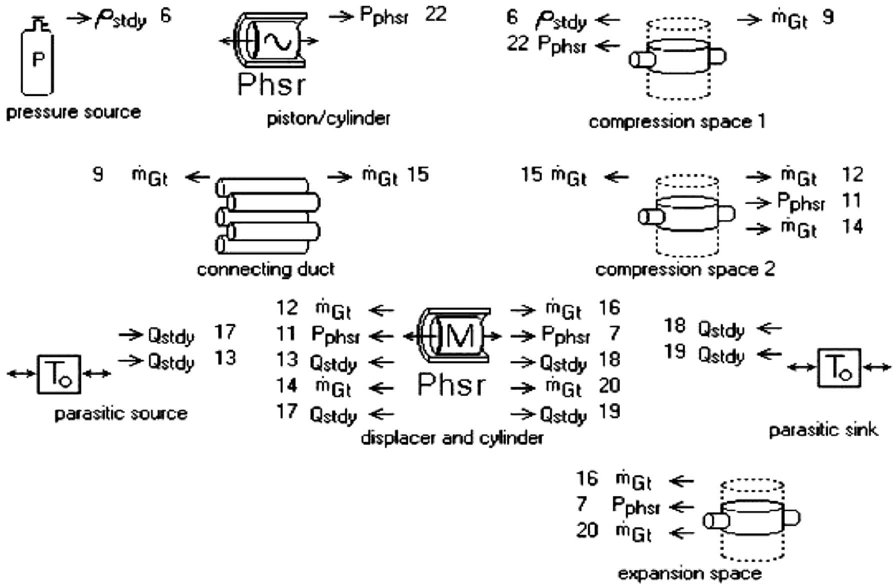

Figure 12. Stirling cooler modeled using SAGE

Table 3. Optimized parameters of Stirling cyrocooler

Optimized Parameters	Values
Q_{lift}	1.516 W
$Q_{rejected}$	26.5 W
W_{pv}	25 W
Cop actual	6.06E-02
Cop theoretical	0.3637
Carnot efficiency	16.7 %
Displacer spring Stiffness	2940 N/m
Amplitude of constrained piston	9.44 mm
Negative facing area	28.5 mm^2
Displacer amplitude	2.784 mm
Displacer phase angle	48.02^0

Design of Cryocooler Using SAGE

The required cryocooler was also designed using SAGE v.11 software package as illustrated in Fig. 12. We are using a Stirling cryocooler for the current analysis. The optimized parameters of the designed cryocooler are shown in Table 3.

CONCLUSIONS

The designed model helped in understanding the various heat flows within the system. The control system with the feedback loop is able to maintain the rover within its required temperature range, and the sensor has minimal parasitic heat input from the cabin. Since the cryocooled temperature of the sensor is way below that of the atmospheric temperature of the Mars environment, there is a heat leak from the surroundings for which we are using MLI and glass for insulation.

The designed Stirling cryocooler is able to accommodate this heat load and still maintain the sensor at around 80 K as required. This was possible only because we incorporated an independent helium loop that diverts flow of the primary working fluid towards the sensor when required.

Designing the thermal management system using the similarity between rovers and electric vehicles was a novel idea, and we have included various additional parts into the whole system like the RTGs, Stirling engine, additional heaters, battery pack, etc. And each of these sub components is designed for its specific purpose, keeping in mind the adverse environmental conditions that each will be exposed to. In all these conditions, the cabin temperature is found to be maintained at around 20°C, even though the atmospheric temperature is varying between 0°C and -100°C on average.

In addition, an additional independent helium loop helped in overcoming the limitation of constantly turning on and off the cryocooler, which has a modest cooldown time to reach the required temperature.

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