Design and Analysis of the Location of Cold and Heat Sources for the Payload's Active Thermal Control System on the Lunar Surface

Hongyu Zhang¹, Yajing Li², Yifei Wang¹, Miaocheng Weng¹,³,⁴, Fang Liu¹,³,⁴,*

1 School of Civil Engineering, Chongqing University, Chongqing 400045, PR China
2 Zhuhai Singyes Green Building Technology Co., Ltd.
3 Key Laboratory of New Technology for Construction of Cities in Mountain Area of Ministry of Education (Chongqing University), Chongqing 400045, PR China
4 Joint International Research Laboratory of Green Buildings & Built Environments, Chongqing 400045, PR China
B Campus, Chongqing University, 83 Shabei Street, Shapingba District, Chongqing. Email: 1418238756@qq.com

Abstract. The payload of the Chang'e-4 biological experiment is used as an object for designing and analyzing the location of cold and heat sources. The research compares and analyzes the energy consumption and temperature uniformity of cooling and heating sources mounted on different surfaces using Thermal Desktop/Sinda Fluent, which may be used to guide the design and operation of active thermal control systems. The results indicate that when the hot and cold sources are mounted on the payload's top surface, the total energy consumption of the active thermal control system is minimized and temperature uniformity is improved.

Keywords. Active thermal control, energy consumption, temperature uniformity, cold and heat sources.

1. Introduction
The thermal control system regulates heat transfer from the payload's inside to its outside. Thermal control systems may be passive or aggressive. The thermal condition of the load is basically unadjustable once detected during the passive thermal control procedure [1]. Active heat control offers the benefits of being extremely flexible and precise. As a result of this, the payload's capacity to adapt and adjust to the external environment and operate is improved.

Domestic and international research on active thermal control numerical simulation computations has largely focused on extensive analyses of active thermal control systems in recent years. Zhou et al. [2] summarized the research on active thermal control systems by demonstrating that the research hotspots were primarily focused on spacecraft thermal control system performance analysis and equipment system optimization, and did not include the design of active thermal control systems during the development phase of the payload model. R. Nadalini [3] et al. presented active thermal control mechanisms for heat dissipation using variable thermal conductivity heat pipes and thermal switches, and validated their logic and dependability using ground thermal simulation tests. Derek W et al. [4] provided an overview and generalization of contemporary spacecraft subsystem temperature management technologies, as well as a detailed assessment of their possible applications and use scenarios. Shao et al. [5] proposed a thermal control design for the Chang'e-3 probe, utilizing a radiative
heat sink during the lunar day phase and a two-phase fluid loop and isotopic heat source during the lunar night phase, and analyzed the thermal control effect using numerical simulations; Li et al. proposed a joint heat dissipation active thermal control method, and the simulation results indicated that this thermal control method performed well. In summary, ongoing thermal control research at the moment is mostly focused on the design and development of thermal control system schemes for actual engineering applications.

However, using peak cold and heat loads to build active thermal control systems wastes energy and overcools or overheats the payload. Simultaneously, to maintain the payload’s internal temperature regulation while responding to exterior climatic changes, the ground must feed the appropriate heat and cold in real time [6]. Since cold and heat sources are positioned on various surfaces, the paper concentrates on the payload model. This data helps design and operate the active thermal control system.

2. Governing Equations and Numerical Simulation

2.1. Governing Equations

The control target parameter of the payload model is temperature, and this paper will establish the heat transfer mathematical model by establishing the heat balance conditions in the space thermal environment where payload model is located. The total energy balance equation of the lunar surface load model is established based on the principle of energy conservation.

\[ Q_1 + Q_2 + Q_3 + Q_4 = Q_5 + Q_6 \]

Where \( Q_1 \) - \( Q_4 \) are the heat gains from solar radiation, reflected solar radiation, lunar infrared radiation, and the heat gain from the heat source inside the spacecraft. \( Q_5 \) is the heat gain from spacecraft radiation, while \( Q_6 \) is the change in the spacecraft’s internal energy.

The total energy balance calculation assumes the payload as a whole. However, in actuality, the payload model’s surfaces have varying azimuthal angles to the Sun and Earth space, and hence different temperatures on each surface. Because of this, each instrument, component, or portion of the payload model has its own heat balancing equation [7]. Currently, the nodal network method is used for spacecraft thermal analysis. The nodal network approach emerged from Oppenhiem’s analogous electrical and thermal modeling principles [8]. Analytic objects are divided into micro-element control bodies of specified dimensions, each considered as an isothermal object with similar thermophysical properties, and labeled as nodes. The heat balance equation 1.9 for each node can be listed.

\[ Q_{sj} + Q_{pj} + \sum_{i=1}^{m} B_{i,j} A_i \varepsilon_i \sigma T_i^4 + \sum_{i=1}^{n} D_{i,j} (T_j - T_i) = (cm)_j \frac{dT_j}{d\tau} + A_{j} \varepsilon_j \sigma T_j^4 \]

Where \( Q_{sj} \) is the heat flow outside the space absorbed by node j. \( Q_{pj} \) is the thermal power consumption of node j. \( B_{i,j} \) is the Gebhardt coefficient. \( D_{i,j} \) is the heat transfer coefficient between node i and j. \( (cm)_j \) is the heat capacity of node j. m is the number of nodes with radiative heat transfer at node j. n is number of nodes with conduction heat exchange with node j. \( \tau \) is the time.

The Monte-Carlo approach is now frequently used to complete computations, considerably enhancing the speed and accuracy of thermal simulations. The solver software SINDA/FLUINT, which is utilized throughout the paper, also adopts this approach.

2.2. Numerical Simulation

2.2.1. Modeling Geometry. Due to the limitation of using the data of Chang’e-4 "Biological Science Experiment Load", the payload model in the initial sample stage was chosen as the object of study. The model is divided into six surfaces, taking into account the different azimuthal angles between the payload model and the Sun and the Moon during one lunar day cycle. The model is shown in figure 1.
2.2.2. **Boundary Conditions.** The preliminary payload model of the lunar surface loading model at The Moon's Farside Von Kármán Crater is studied. The model is furnished with animal and plant life, as well as supporting instruments and equipment, and is exposed to external space environments such as high vacuum, microgravity, and extremely cold lunar surface temperatures (-180°C). Therefore, to maintain the survival of biological organisms and normal equipment operation, the inside temperature must be kept between 20°C and 30°C. However, due to space and budget constraints, the internal thermal control system is fitted with a small-scale, lightweight thermal control system. The active thermal control measures of semiconductor refrigeration and electric heating, which are inexpensive and straightforward to install and operate, are adopted for temperature management in this study. Table 1 summarizes the lunar surface load model's environmental conditions.

![Figure 1. Schematic diagram of the payload model.](image1)

**Figure 1.** Schematic diagram of the payload model.  

![Figure 2. Payload internal extreme temperature and peak cold load curves.](image2)

**Figure 2.** Payload internal extreme temperature and peak cold load curves.

**Table 1.** Environmental condition table of payload model.

| Type                        | Parameter                                  |
|-----------------------------|--------------------------------------------|
| Model                       | Temperature control target                 | 20–30°C                                    |
| Space environment           | Location                                   | Von Karman crater (177.6°E, 45.5°S)       |
|                             | One lunar daily cycle                      | 655.722 hours                              |
| Thermal control measures    | Passive thermal control measures           | MLI+ coating                               |
|                             | Inner surface black paint (0.9, 0.9)       |                                          |
|                             | Outer surface SiO2-Al (0.9, 0.1)           |                                          |
|                             | Active thermal control measures            | Semiconductor refrigeration               |
|                             |                                            | Electric heating                           |

3. **Design and Analysis of Cold and Heat Sources Installation Position**

3.1. **Comparison of Mounting Surfaces of Cold and Heat Sources**

During cooling and heating, the temperature of the payload model nodes must be near to the temperature control interval boundary. As a result, the internal cooling and heat calculation is only possible via software simulation, constantly changing the internal cooling and heat size. Figure 2 shows the highest temperature and peak cooling load inside the payload model at the extreme hot condition of 281.028.

From figure 2, The predicted peak cooling load under very hot conditions (281.028) of the payload model was Z1, X1, Y1, X2, Y2, X2, and Z2 in descending order of surface position. The peak cooling load calculation value is -30.15W when the heat source is situated on the Z2 surface of the payload model. So the payload model's bottom surface Z1 is the least suitable for installing cold and heat sources. The
heat source is mounted on the $Z_2$ surface at the top of the payload model, reducing the peak cooling demand and ensuring the most uniform temperature distribution. Thus, $Z_2$ on the payload model's top surface is the best place to install cold and heat sources.

In practice, the payload model is generally linked to the mothership. So the payload model's bottom surface $Z_1$ is the least favorable mounting surface for the cold and heat sources, and its top surface $Z_2$ is the most favorable. The other five surfaces except $Z_1$ are installed together as the mixed mounting surface of the cold and heat source.

3.2. Energy Consumption Analysis
In a lunar day operating cycle, the peak heat load $Q_h$ is 3.05 W; the peak cooling load $Q_c$ is -31.04 W. The no operation strategy condition is cooling at the peak cooling load during the cooling period and heating at the peak heat load during the heating period. The cooling and heating sources are installed on different surfaces of the payload model, and the time-by-time cooling and heating loads are calculated as shown in the table 2.

| Working condition        | Cooling energy consumption /KJ | Heating energy consumption /KJ | Total energy consumption /KJ | Energy-saving efficiency |
|--------------------------|--------------------------------|-------------------------------|-----------------------------|-------------------------|
| No operation strategy    | 41870.88                       | 3085.69                       | 44956.57                    | /                       |
| The most unfavorable surface | 28896.37                   | 3692.70                       | 32589.07                    | 27.50%                  |
| The most favorable surface  | 28219.94                   | 3654.76                       | 31874.70                    | 29.09%                  |
| Mixed surfaces           | 28360.62                     | 3619.35                       | 31979.97                    | 28.86%                  |

From table 2, it can be obtained that the payload model consumes the most total energy under one lunar day operation cycle with no operation strategy. The principal heat transport modalities in microgravity are conduction and radiation. This is because the top surface faces the Sun and thus receives more heat from space. The bottom surface faces the Moon, which is less affected by heat flow from outer space. Heat and cold sources on top of the payload model can better resist heat conduction and radiation, resulting in the lowest overall energy consumption and the highest efficiency, 29.09%. In this case, the heat and cold sources are on the payload model's bottom surface, causing higher overall energy consumption and the lowest energy saving efficiency of 27.50%. It is recommended that the cold and heat sources be placed on the payload model's top surface $Z_2$. 

3.3. Temperature Field Analysis
To compare and analyze the temperature field uniformity of nodes within the payload model when different cold and heat sources installation wall surfaces are used (the most unfavorable surface, the most favorable surface, and a mixed surface), the interior of the payload model is divided into six layers along the $Z$-axis direction, from bottom to top as layer I, layer II, layer III, and layer IV. As shown in figure 3.
Figure 3. Temperature field stratification diagram.

Based on the payload model of von Karman crater, the mean temperature variation curves of each layer in the Z direction within the payload during a lunar daily cycle are analyzed. From Figure 4, it can be seen that the payload model has the smallest difference in the mean value interval of all nodes temperature in the interior for the mixed surfaces during a lunar day operation cycle, whether in the cooling or heating time. From the total mean value interval of temperature of all nodes in the interior compared to the design temperature requirement (20-30°C), the mixed surfaces are the closest, and from the mean value of temperature of all nodes in the interior layers compared to the design temperature requirement (20-30°C), the mix surfaces reach the temperature control target for the most periods.

The average temperature interval difference of all internal nodes is the smallest for mixed surfaces, followed by the most favorable surface, and the highest is the least favorable surface in a lunar day operation cycle of the payload model. The mixed surfaces were the closest to the design temperature (20-30 °C), followed by the most favorable and the least favorable. In terms of time required to reach the temperature control objective (20-30 °C), the mixing surface takes the greatest time, followed by the most favorable surface, and finally the least unfavorable.
Figure 4. The cold and heat sources are installed on (a) surface $Z_2$ (b) surface $Z_1$ and (c) mix surfaces and the average temperature diagram of each layer in $Z$ direction inside the payload.

Comparison of cold and heat source surfaces (unfavorable, favorable, and mixed) yielded the average temperature of each layer in the payload model's $Z$ direction. A more pronounced internal temperature stratification was seen when the cold and heat sources were put on the payload model's surface $Z_1$ (the least favorable surface). The interior temperature stratification is more consistent when the heat source is situated on the $Z_2$ surface (the most favorable surface) of the payload model. The internal temperature stratification was most uniform and the effect was highest when both heat and cold sources were positioned on the other five surfaces (mixed surface) except for surface $Z_1$.

4. Conclusion
The cold and heat sources are installed on the top surface $Z_2$ of the payload model as the most favorable surface. When the cold and heat sources are installed on face $Z_2$, the greatest temperature and smallest temperature span interval are the smallest, and the temperature distribution is the most uniform, compared to the other five cold and heat sources installation faces.

To reduce the active thermal control system's energy consumption, the cold and heat source should be installed on the top surface $Z_2$ of the payload model, that is, the most favorable surface for installing the cold and heat source. The model's total energy consumption was the lowest and its energy saving efficiency was the highest, at 29.09%. The mixed surface cooling and heating source has a slightly lower energy saving efficiency of 28.86%. The source of cooling and heating installed on the least favorable surface saves the least energy at 27.50%.

In terms of payload interior temperature field uniformity, the best results were obtained by concurrently installing cold and heat sources on five surfaces without $Z_1$ (mixed installation surfaces). This is followed by $Z_2$ and $Z_1$.

Finally, considering the operability of the active thermal control system's installation and the analysis results for the active thermal control system's energy consumption, it is recommended that the cold and heat source be installed on the top surface $Z_2$ of the payload model, that is, the most favorable surface for the cold and heat source's action.

Acknowledgments
Funding: This work was also supported by the Third Pre-research Projects of the Civil Space Project from China National Space Administration(CNSA), under the project of "The Key Technology for the Construction of Micro-ecospheres Adapted to the Lunar Environment".
References

[1] Clou, S D, et al. 2015 "Performance and Control of a Pulse Thermal Loop Heat Transport System." *Journal of Thermophysics and Heat Transfer* 29(4)(2015) pp 1-9.

[2] Zhao C Y, et al. 2018 "Analysis of Development Trend of Lentinan Research Based on the Literature of Web of Science." *Edible Fungi of China*.

[3] Nadalini R, Bodendieck F. 2006 "The thermal control system for a network mission on Mars: The experience of the Netlander mission." *Acta Astronautica* 58(11)(2006) pp 564-575.

[4] Hengeveld D, et al. 2010 "Review of Modern Spacecraft Thermal Control Technologies." *HVAC&R RESEARCH* 16(2)(2010) pp 189-220.

[5] Shao X. "Heat Pipe Applications and Test in Chang'e-1 Satellite." *Spacecraft Engineering*.

[6] Jia, Y, et al. 2018 "Scientific Objectives and Payloads of Chang'E-4 Mission." *Chinese Journal of Space Science*.

[7] Hou Z, et al. 2007 *Spacecraft thermal control technology*. Press of University of Science and Technology of China.

[8] Oppenheim A V, and Lim J S. 1981 "The importance of phase in signals." *Proc IEEE* 69.5(1981): pp 529-541.