Research on space microwave energy reception technology based on electromagnetic-thermal-DC conversion

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Abstract. A new microwave energy reception method is proposed for the wireless energy transmission needs of lunar rovers combined with the lunar environment, i.e. collecting thermal energy through microwave absorbing materials, and then converting thermal energy into direct current by using temperature difference power generation devices. The article analyses the two conversion processes, microwave-thermal and thermal-DC, separately. Under the approximate condition that the temperature at both ends of the absorbing material is regarded as equal, the two conversion processes are linked by energy conservation, which theoretically leads to the temperature and total efficiency of the system at steady state. The temperature and total efficiency of the system are initially obtained by numerical simulation with respect to the thickness of the absorbing material, the receiving area and the input power density by selecting the parameters of the carbon and iron composite material at 10 GHz. The results show that there is an optimum thickness of absorbing material for a certain input power density and receiving area, which results in the highest system efficiency. The larger the receiving area and input power density in a certain range, the higher the efficiency, but beyond a certain range the system efficiency shows a decreasing trend. Also the theory and the actual will produce a large deviation when temperature is high. The article concludes that this energy receiving method has great potential for application in the space environment based on the excellent wave absorbing materials and thermoelectric components but further research is needed.

1. Introduction
After half a century of development, microwave energy transmission technology has a wide range of application scenarios. So far, countries around the world have completed a large number of experiments on terrestrial energy transmission systems as well as air-to-ground energy supply. While there are fewer scenarios where the energy receiving end is in an extraterrestrial space environment, such as inter-satellite energy transmission and power supply for space equipment, etc. These plans have not been implemented by engineering. In the near future, China will face the technical challenge of wireless energy transmission to the lunar rover. Combined with the characteristics of the high vacuum in space, in order to avoid the risk of damage to the rectifier diode from high irradiation in the space environment, this paper proposes a novel electromagnetic-thermal-electric microwave energy collection method. Theoretical analysis and simulation of the various physical processes involved have been carried out, providing a new idea for the reception and use of microwave energy.
2. Microwave-thermal-DC working principle
The lunar rover is unable to receive solar energy during in-crater exploration due to terrain occlusion. And it has been demonstrated\cite{1} that microwave energy transmission is a better way to supply energy. Unlike the traditional antenna receiving rectification, this paper proposes a new microwave energy reception method for the high vacuum and high irradiation characteristics of the lunar environment, including the conversion of incident microwave energy into thermal energy and the using of temperature difference power generation devices to convert thermal energy into direct current. This avoids the risk of diode damage caused by space irradiation, simplifies the structure and reduces costs. The logical structure of this energy reception method is shown in Figure 1 and its physical schematic is shown in Figure 2.

![Fig 1. Logic structure of microwave-heat-DC conversion](image1)

![Fig 2. Physical schematic diagram of microwave-heat-DC](image2)

2.1 Microwave absorption heating process
For materials with complex permittivity and complex permeability of $\varepsilon = \varepsilon' - j\varepsilon''$ and $\mu = \mu' - j\mu''$, the wave impedance is:

$$Z = \sqrt{\frac{\mu' - j\mu''}{\varepsilon' - j\varepsilon''}}$$  \hspace{1cm} (1)

The propagation constant of an electromagnetic wave of angular frequency $\omega$ in material is\cite{2}:

$$\gamma = j\omega \sqrt{(\mu' - j\mu'') + (\varepsilon' - j\varepsilon'')} = \alpha + j\beta$$  \hspace{1cm} (2)

where: $\alpha$ is the loss constant and $\beta$ is the propagation phase constant.

The reflectance of material to an incident wave from a vacuum (with a wave impedance of $Z_0$) is:
Fig 3. Schematic diagram of plane wave incident lossy material

As shown in Figure 3, an ideal electrical wall is set up behind a wave-absorbing material of thickness $d$. Assuming positive incidence of electromagnetic waves, the total normalised thermal energy absorbed by the wave-absorbing material is:

$$Q_{\text{en}} = (1 - |\Gamma_{\text{en}}|^2)$$  \hspace{1cm} (4)

where the reflection coefficient $\Gamma_{\text{en}}$ is:

$$\Gamma_{\text{en}} = \frac{Z_{\text{en}} - Z_0}{Z_{\text{en}} + Z_0} = \frac{Z \tanh(\gamma d) - Z_0}{Z \tanh(\gamma d) + Z_0}$$  \hspace{1cm} (5)

There are forward and reverse waves in the spatial region, and based on multiple reflection theory\cite{3}, and normalized to the incident field magnitude, the forward and reverse wave electric fields within the material are calculated as:

$$E^+(z) = \frac{(1 - \Gamma) (e^{j\beta z - \alpha z})}{1 + \Gamma e^{-2j\beta d - 2\alpha d}}$$  \hspace{1cm} (6)

$$E^-(z) = \frac{(\Gamma - 1) (e^{j\beta z + \alpha z - 2j\beta d - 2\alpha d})}{1 + \Gamma e^{-2j\beta d - 2\alpha d}}$$  \hspace{1cm} (7)

The corresponding normalised energy flow density is:

$$W(z) = \frac{1}{2} \text{Re} \left\{ \left[ E^+(z) + E^-(z) \right] \left[ \frac{E^+(z) + E^-(z)}{Z} \right]^* \right\}$$  \hspace{1cm} (8)

The resulting electromagnetic heat source density at different locations within the material along the propagation direction $z$ is:

$$W_{\text{en}}(z) = -W'(z)$$  \hspace{1cm} (9)

2.2 Thermoelectric conversion process

Thermoelectric conversion is also known as temperature differential power generation. A typical temperature differential power generation device consists of multiple Π-type thermoelectric units connected in electrical series and thermal parallel, where the Π-type thermoelectric unit consists of n-type and p-type electric couple arms connected to the hot and cold end electrodes\cite{4}, as shown in Figure 4.
According to the Seebeck effect\(^5\), when there is a temperature difference \(\Delta T\) between the two ends of a thermoelectric device, an electric potential \(V\) is generated:

\[
V = S_{np} \Delta T
\]  

(10)

A current is then generated in the circuit:

\[
I = \frac{V}{R + R_L}
\]  

(11)

This gives the electrical power as:

\[
P = I^2 R_L = \frac{S_{np}^2 \Delta T^2}{(R + R_L) R_L}
\]  

(12)

Where: \(S_{np}\) is the total Seebeck coefficient of the n- and p-type thermocouple arm thermoelectric material. \(R\) is the internal resistance of the thermoelectric device. \(R_L\) is the external load size.

In the ideal case, i.e. without considering the thermal resistance and the change in heat generated by the thermal resistance at the interface between the electrocouple arm of the device and the electrode connection, the energy \(Q_h\) conducted from the outside to the hot end per unit time consists of the sum of the heat conducted from the hot end to the cold end and the heat generated by its own Joule heat as well as the Pall paste effect\(^6\):

\[
Q_h = \frac{S_{np}^2 T_h (T_h - T_c)}{2R} - \frac{S_{np}^2 (T_h - T_c)^2}{8R} \left( \frac{k_p A_p}{l_p} + \frac{k_n A_n}{l_n} \right) \left( T_h - T_c \right)
\]  

(13)

where \(T_h\) and \(T_c\) are the temperatures at the hot and cold ends of the device, and \(k, A, l\) are the thermal conductivity, cross-sectional area and length of the crystal block.

The thermoelectric conversion efficiency of a thermoelectric device is the ratio of the electrical power output to the thermal energy input:

\[
\eta = \frac{P}{Q_h}
\]  

(14)

When the device internal resistance \(R\) and external resistance \(R_L\) size equal device has the maximum conversion efficiency. From the formula (13) ~ (14), the maximum conversion efficiency is:

\[
\eta_{max} = \frac{T_h - T_c}{T_h} \sqrt{1 + ZT_{ave} \frac{1}{T_h}} - \sqrt{1 + ZT_{ave} + \frac{T_c}{T_h}}
\]  

(15)

where the average thermoelectric superiority value (dimensionless) is:

\[
ZT_{ave} = \frac{S_{np}^2 \sigma}{k} \ave = \frac{S_{np}^2 \sigma}{k_p A_p \ave + k_n A_n \ave} \cdot \frac{T_h + T_c}{2}
\]  

(16)

\(S_{np}, \sigma, k\) are the Seebeck coefficient, electrical conductivity and thermal conductivity of the crystals respectively.
Due to the limitations of material theory, the combination of electrical conductivity, thermal conductivity and Seebeck coefficient of natural materials makes it difficult to achieve a high value of thermoelectricity. The current high-efficiency thermoelectric materials with mature applications include bismuth telluride and aluminium telluride, whose maximum thermoelectric conversion efficiency generally does not exceed 10%.

3. Analysis of microwave energy reception systems

3.1 Theoretical analysis

The electromagnetic-thermal-electric energy conversion system includes the physical processes of microwave energy absorption, material heating and warming, heat conduction, dissipation and electrical energy conversion, involving multidisciplinary expertise, which makes research and analysis more difficult. In order to simplify the overall analysis process to explore the basic laws of energy conversion, we make the following two assumptions in the paper: 1) Assuming the absorbing material and the hot end of the thermocouple between the ideal thin layer with ideal conductivity and thermal conductivity. In practice, some thermally conductive substance is required for bonding, such as thermally conductive silicone grease; 2) The effect of temperature change on the complex dielectric constant, complex magnetic permeability of the wave absorbing material and the Seebeck coefficient, thermal conductivity and electrical conductivity of the thermoelectric device is not considered; 3) It is assumed that good cooling measures exist at the cold end of the temperature differential power generation device, which can always be consistent with the overall temperature of the lunar exploration vehicle. The maximum temperature in the lunar crater is 330 K, the minimum 170 K \[7\], and its average value is about 250 K. Considering the existence of heat generation in the lunar rover itself, which is slightly higher than the ambient temperature, the temperature of the cold end of the thermoelectric devices is considered to be 273.15 K, i.e. 0°C, in the subsequent analysis.

Fig 5. Schematic diagram of thermal steady state (Attributed to a thermoelectric unit)

The absorbing material of thickness $d$ will generate heat and exchange heat with its contact thermoelectric parts under the continuous vertical incidence of a plane wave of power density $P$. After a certain time the system will enter thermal equilibrium, as shown in Figure 5. Let impute to a thermoelectric unit of absorbing material receiving area for $S$, then by the basic law of conservation of energy can be obtained: absorbing material temperature stability, unit time absorbed electromagnetic heat energy is equal to $z = 0$ at the environment of thermal radiation and $z = d$ at the heat conducted to the thermocouple of the sum, that is:

$$Q_{em} = P_{rad} + Q_h$$  \hspace{1cm} (17)

where:

$$Q_{em} = (1 - |\Gamma_{in}|^2)PS$$  \hspace{1cm} (18)

$$P_{rad} = S\sigma[T^4(0) - T^4]$$  \hspace{1cm} (19)
\[ Q_h = \frac{S_{np}^2 T(d) (T(d) - T_e)}{2R} - \frac{S_{np}^2 (T(d) - T_e)^2}{8R} \left( k_p \frac{A_p}{l_p} + k_n \frac{A_n}{l_n} \right) \left(T(d) - T_e\right) \]  

(20)

The difference between the temperature \(T(0)\) and \(T(d)\) at the two boundaries of the absorbing material at thermal steady state can be investigated using multi-physics field simulation software\(^9\). The thickness of the absorbing material is set to a skin depth of 5.8mm (according to electromagnetic theory, the optimum thickness of the material is generally less than a skin depth), and the simulation results show that at an incident power density of \(10^5\text{W/m}^2\), the temperature at both ends of the material is about 600 K at thermal stability, and the temperature difference between the two ends does not exceed 4 K. Therefore, it can be assumed that the temperature at both ends of the material is approximately equal, i.e.: considering both \(T(0)\) and \(T(d)\) as \(T\), then equation (17) can be written as:

\[ S\varepsilon[T^4 - T_e^4] + \frac{S_{np}^2 T(T - T_e)}{2R} - \frac{S_{np}^2 (T - T_e)^2}{8R} \left( k_p \frac{A_p}{l_p} + k_n \frac{A_n}{l_n} \right) (T - T_e) - \left[ 1 - \left( \frac{Z \tanh(\gamma d) - Z_0}{Z \tanh(\gamma d) + Z_0} \right)^2 \right] PS = 0 \]  

(21)

Then the temperature \(T\) can be solved to obtain the heat flow rate \(Q_h\) of the thermoelectric component and the thermoelectric efficiency \(\eta_{teg}\):

\[ Q_h = \frac{S_{np}^2 T(T - T_e)}{2R} - \frac{S_{np}^2 (T - T_e)^2}{8R} \left( k_p \frac{A_p}{l_p} + k_n \frac{A_n}{l_n} \right) (T - T_e) \]  

(22)

\[ \eta_{teg} = \frac{T - T_e}{T} \sqrt{1 + \frac{S_{np}^2 \sigma(T + T_e)}{2(k_p \frac{A_p}{l_p} + k_n \frac{A_n}{l_n})}} - 1 \]  

(23)

The final total efficiency is:

\[ \eta = \frac{Q_h \eta_{teg}}{PS} \]  

(24)

3.2 Numerical simulation

At present, the materials available on the market that are suitable for absorbing microwave energy and heating are mainly SiC, carbon-based materials, ferrite and their mixtures. These materials satisfy both the impedance matching to reduce reflection loss as far as possible and also have a considerable loss factor to reduce the thickness required for electromagnetic-thermal conversion. In this paper, Fe/C material\(^10\) was chosen as the absorbing material with relative complex permittivity and complex permeability of 7.8-j3.9 and 2-j0.2 at 10 GHz. For the thermoelectric components, the thermoelectric semiconductor parameters provided by Sagaray were used and their measured data at 418 K are shown in Table 1.

| Material       | Resistivity \((10^6\Omega\text{m})\) | Seebeck coefficient \((\mu\text{V/K})\) | Thermal conductivity \((\text{W/mK})\) | Arm length (mm) | Cross-sectional area \((\text{mm}^2)\) |
|----------------|----------------------------------|--------------------------------------|--------------------------------------|----------------|-----------------|
| P-type crystal | 1.9                              | 209.8                                | 1.2865                               | 2              | 4               |
| N-type crystal | 1.611                            | -205.4                               | 1.645                                | 2              | 4               |

*Table data measured at 418K

After determining the parameters of the absorbing material and the thermoelectric components, equations (21)–(24) are simulated in matlab to investigate the effects of the size of the absorbing material (thickness, receiving area) and the incident power density on the efficiency of the system and the temperature of the absorbing material, respectively.
3.2.1 Influence of the size of the absorbing material (thickness, reception area) on the efficiency of the system and the temperature of the material.

At an incident wave power density of $10^4\text{W/m}^2$, the relationship between system efficiency and material thickness and receiving area is shown in Figure 6. It can be seen that for a given receiving area $S$, there is an optimum thickness making the highest energy conversion efficiency. At the same thickness, the total efficiency continues to rise as the receiving area increases.

Fig 6. The total efficiency of the system varies with the thickness of the material and the receiving area ($A$ is the area of the hot end of the individual thermocouple)

To investigate the effect of thickness on material temperature and system efficiency separately, the receiving area was set to 5$A$ and the simulation results are shown in Figure 7. It can be concluded that with other conditions remaining unchanged, the temperature of the absorbing material and the total system efficiency follow the same trend as the material thickness, and there is an optimum thickness ($d=2.71\text{mm}$) that makes the system efficiency the highest. As the material thickness continues to increase, the total system efficiency and material temperature tend to remain constant.
Fig 7. The influence of thickness on microwave energy conversion system
Considering that the thermal radiation term of the absorbing material is also positively related to the material area and temperature, the total efficiency cannot increase without limit as the receiving area \( S \) continues to increase. To investigate the effect of the receiving area \( S \) on the microwave energy conversion system, a thickness of \( d = 2.71 \) mm (the optimum thickness in Figure 7) was selected and the simulation results are shown in Figure 8.

Fig 8. The influence of receiving area on microwave energy conversion system
As can be seen in Figure 8, the temperature continues to increase as the material receiving area increases, but the rise tends to slow down. The overall efficiency of the system stops rising and starts to fall slightly when the material receiving area reaches approximately 75 times the cross-sectional area of the thermocouple. It is worth noting that in practice, when the material receiving area is much larger than the thermocouple cross-sectional area, the temperature may be unevenly distributed in the direction perpendicular to the thickness, resulting in some deviation from the actual numerical simulation results.

3.2.2 Effect of incident power density on system efficiency and material temperature
Since it is assumed that the absorption properties of the absorbing material do not vary with temperature, the total system efficiency depends only on the space heat radiation efficiency and the thermoelectric
conversion efficiency. In the simulation, $d$ was chosen to be 2.71mm, $S$ was 5 times the thermocouple cross-sectional area. Figure 9 shows the relationship between temperature and total system efficiency as functions of input power density.

![Temperature vs. Efficiency](image)

**Fig 9.** The influence of input power density on microwave energy conversion system

The material temperature and thermoelectric efficiency increase with the increase of input power density, but the trend of increase will become slower. When the input power density increases to a certain level (about $1.8 \times 10^6$W/m$^2$), the total system efficiency no longer continues to increase but begins to slightly decrease. In addition, the simulation considers that there is ideal heat dissipation at the cold end of the thermocouple, while in practice it is not easy to dissipate heat at high temperatures. This can lead to large deviations from the simulation model in this paper when the input power density and temperature are high. In practice it is not possible to achieve the high efficiency shown in Figure 9.

4. Conclusion

This paper proposes a new microwave-thermal-electric energy conversion method which is simpler and cheaper than the traditional energy receiving method and can avoid the risk of irradiation damage to rectifier diodes for microwave energy harvesting in space environment conditions. In study, the energy conservation equation is established under certain assumptions. The influence trends of the absorbing material size and input power density on the system temperature and efficiency are obtained by numerical simulation. With other factors fixed, there exists an optimal value for the thickness of the absorbing material, which makes the total system efficiency the highest. While with the increase of the receiving area of the absorbing material and the incident microwave power density, the rising trend of the material temperature and thermoelectric efficiency gradually becomes slower. When they increase to a certain degree, the total system efficiency starts to decrease due to the sharp enhancement of the spatial thermal radiation. However, the research process assumes the existence of ideal heat dissipation at the cold end of the thermoelectric device and does not consider the variation of thermoelectric device and wave-absorbing material parameters with temperature. Therefore, the research results have certain limitations and further in-depth research and improvement are required subsequently.

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