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RESEARCH ARTICLE

Efficient microwave self-heating of lunar regolith for *In Situ* Resource Utilization (ISRU): methods and system validation

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Abstract To address the demand for large-scale utilization of lunar resources, this study develops an efficient microwave heating approach for lunar regolith. Based on the dielectric properties of lunar regolith—low loss at low temperatures and high loss at high temperatures—three high-efficiency microwave heating methods were proposed. These methods include increasing electric field strength, delimiting heating temperature ranges, and enriching high-loss lunar regolith minerals. A microwave heating system was established to validate the electric field increase method, with self-heating experiments conducted at 2.45 GHz and 300−800 W. The results show that: at 800 W microwave power, the temperature of the cavity can reach 1259°C within 420 s, and lunar regolith simulant can be melted. Compared with industrial microwave equipment, the proposed system achieves superior energy efficiency without requiring susceptor-assisted heating. It consequently removes the necessity of transporting auxiliary materials from Earth. This microwave heating approach provides a practical and cost-effective solution for early lunar surface construction and *in situ* utilization of lunar surface resources.

Keywords ISRU, microwave heating, dielectric properties, compression waveguide

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1 Introduction

Lunar exploration has shifted from a focus solely on understanding the lunar to equal emphasis on both exploration and utilization. As the closest celestial body to Earth, the lunar boasts three categories of exploitable resources: positional, environmental, and material resources (Song et al., 2019). China has proposed the International Lunar Research Station (ILRS) program. Lunar resource utilization is the primary goal of the third phase of ILRS construction. The objective is to gradually realize the development and utilization of lunar resources such as energy and materials (Pei et al., 2020). *In Situ* Resource Utilization (ISRU) primarily comprises three aspects: energy acquisition, mineral extraction, and lunar-based construction, operation and maintenance (Pei et al., 2024). It can eliminate the high-cost Earth-Lunar transportation (Goulas and Friel, 2016).

Heating lunar regolith was a key link in resource utilization. It played an important role in sintering, gas extraction, water extraction, and oxygen production. Sintering was a lunar regolith consolidation method that required no additional materials. It was regarded as an ideal approach for early lunar surface construction (Liu et al., 2025). Thus, various heating methods have been widely used in lunar regolith sintering research. Solar sintering (SS), laser sintering (LS), spark plasma sintering (SPS), and microwave sintering (MS) were the main sintering methods. SS was an effective manufacturing

method on the lunar surface. It had a high forming rate and low cost, making it more suitable for in situ manufacturing of large lunar structures. But sintered products generally had high porosity, insufficient densification, and poor mechanical properties (Zhang et al., 2025). LS could produce structures of different sizes and shapes with practical value (Fateri and Gebhardt, 2015). Yet the low thermal conductivity of lunar regolith limited its sintering thickness. SPS featured high heating-cooling rates, short processing times, and low sintering temperatures (Zhang et al., 2020). But its complex equipment posed significant challenges for engineering applications (Han et al., 2024). MS differed from traditional SS and LS in heating principle. It converted microwave electromagnetic field energy into thermal energy to achieve volume heating. This avoided the problem of low thermal conductivity in lunar regolith or lunar regolith simulant. It also had the advantages of low energy consumption, fast heating rate, and simple equipment composition. Microwaves were considered a more feasible method for ISRU. Extensive research had been conducted on microwave heating of lunar regolith simulant. Most studies focused on the effects of mineral composition (Zhang et al., 2024; Wang et al., 2025a, 2025b), electric field intensity (Go et al., 2025), sintering temperature (Kim et al., 2021), power (Lim and Anand, 2019), and pre-sintering pretreatment (Jin et al., 2024) on the mechanical properties of lunar regolith formed products. However, data on the interaction between microwaves and returned lunar regolith samples was lacking (Allan et al., 2013). It was currently unknown whether crystal structure or elemental composition was the primary factor influencing dielectric constant. An analytical system was urgently required, which ranged from the microscopic electronic polarization mechanism to the macroscopic lunar regolith permittivity model and further to the microwave heating effect (Fa, 2023). Previous studies mainly focused on the variation law of macroscopic dielectric properties of lunar regolith simulants with temperature under a specific microwave frequency. It was used to evaluate the ability to absorb microwaves and the feasibility of heating. Under a microwave frequency of 2.45 GHz, the variation of permittivity of lunar regolith simulant showed a tendency to increase with temperature (Meng et al., 2011; Prabhu, 2018; Kim et al., 2024). The loss tangent ($\tan\delta$) increased with temperature, which allowed more microwave absorption at higher temperatures (Kim et al., 2024). The coupling effect between lunar regolith simulant and microwaves in the low-temperature range was poor. Thus, direct microwave heating was difficult to initiate. Therefore, SiC was often used as a susceptor for auxiliary heating to improve heating efficiency in the low-temperature range (Jin et al., 2024; Go et al., 2025; Liu et al., 2025; Wang et al., 2025a). This method was widely applied in microwave sintering. The heat distribution within the sample in the sintering process was maintained (Oghbaei and Mirzaee, 2010; Bhattacharya and Basak, 2016). But the transportation cost of transporting susceptors such as SiC to the lunar was extremely high (Duke et al., 2003; Tsubaki et al., 2024). Therefore, the self-heating of lunar regolith by microwaves without the use of susceptors could reduce the cost of ISRU.

Based on the principle of microwave heating and the coupling mechanism between lunar regolith and microwave fields. The high-efficiency microwave self-heating method was proposed. This method involved increasing electric field intensity, defining heating temperature ranges, and enriching high-loss lunar regolith minerals. Experimental verification of the proposed method for increasing electric field intensity via a compressed waveguide was carried out. A high-efficiency microwave heating system was established. Microwave self-heating experiments were conducted using high-titanium lunar regolith simulant. The heating effect of enhanced electric field intensity was analyzed. The influence of microwave power on the temperature rise rate was investigated.

2 Microwave heating principles of lunar regolith and high-efficiency methods

2.1 Microwave heating principles of lunar regolith

Microwave volumetric heating was achieved based on the interaction between materials and electromagnetic fields. It differed from traditional heating, where heat was transferred from an external heat source to the interior of materials. Microwave heating occurred inside the material. Its heating rate was independent of heat transfer from external heat sources and the thermal conductivity of the material itself. The internal temperature of materials heated by microwaves was usually higher than the surface temperature (Bhattacharya and Basak, 2016). Especially for materials with low thermal conductivity such as lunar regolith (Cremers and Hsia, 1974) significant advantages were demonstrated by microwave heating. The principles of conventional heating of lunar regolith and microwave heating of lunar regolith were depicted in Fig. 1.

The basis of microwave heating was the material's response to the alternating electromagnetic field of microwaves. Material responses to electric and magnetic fields were measured by permittivity (ε') and dielectric

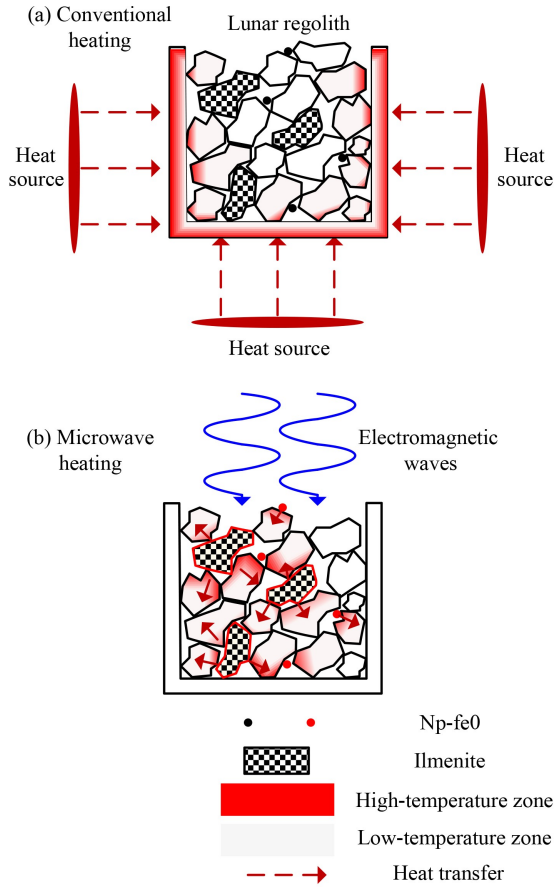


Fig. 1 Principles of microwave heating.

loss (ε''), as well as permeability (μ') and magnetic loss (μ''). Dielectric loss (ε'') and magnetic loss (μ'') determined the material's ability to convert electrical energy and magnetic energy into thermal energy (Bhattacharya and Basak, 2016). For most materials (e.g., ceramics, minerals), the magnetic permeability loss angle $\tan\delta \to 0$ (Bhattacharya and Basak, 2016). Thus, only the dielectric loss (ε'') of lunar regolith was discussed in this study. Based on the microwave penetration depth (D_p) and loss tangent ($\tan\delta$), materials were classified into three categories (Reflector, Microwave transparent, and Microwave absorber) (Oghbaei and Mirzaee, 2010). Microwave absorbers were also high-loss materials, with a loss tangent $\tan\delta > 0.1$ or penetration depth (D_p) of several centimeters (Bhattacharya and Basak, 2016).

An expression for the microwave-lunar regolith interaction had not been established. Thus, this study was conducted based on the electrical heating model of ceramics in microwave fields. The model was proposed by Meek (1987). Three key parameters were presented: the power per unit volume, the depth (skin depth) of microwave energy penetration, and the approximate heating rate of the material in microwave fields. The heating rate (ΔT) was derived without considering any heat losses such as heat conduction, heat convection, heat radiation, and state changes. These parameters were shown in Eqs. (1) to (3):

$$P = KfE^2k'\tan\delta, \tag{1}$$

$$D_g = 1/2\pi\mu cf, \tag{2}$$

$$\Delta T \simeq 8\times10^{-12}fE^2k'\tan\delta/\left(\rho C_g\right), \tag{3}$$

where P = power per unit volume; K = constant; f = frequency of radiation; E = electric-field intensity; k' = relative permittivity; $\tan\delta$ = loss tangent; D_p = depth (skin depth) of microwave energy penetration; μ = magnetic permeability; c = electrical conductivity; ΔT = heating rate; ρ= density of material, C_p = heat capacity.

It could be seen from the above equations that under microwaves of a specific frequency, the heating effect of the material was related to the electric field strength (E), relative permittivity (k'), and loss tangent ($\tan\delta$). In addition, it was suggested by Meek et al. that regions with high density would reduce the coupling effect between the microwave field and the material (Meek, 1987). The microwave field would act more intensively on regions with low density and low relative permittivity. Thus, theoretically, uniform sintered materials would be generated by microwaves.

The primary mineral types on the lunar include basalt (pyroxene, ilmenite, olivine), anorthosite (anorthite), and KREEP, among others. The chemical composition of these minerals is predominantly SiO_2, TiO_2, Al_2O_3, and similar elements, as shown in the Table 1 (Wu et al., 2023; Li et al., 2024).

The dielectric properties of each phase in composite materials were different. Thus, the coupling effects between each phase of the composite materials and microwaves were also different. Therefore, the interaction process between composite materials and microwaves was more complex (Taylor and Meek, 2005). Based on the analysis of the main chemical compositions of the lunar regolith return samples, it was concluded that lunar regolith could be regarded as a composite material. Thus, the interaction between lunar regolith and microwave fields needed to be explored and optimization methods needed to be proposed to enhance the microwave heating effect.

2.2 High-efficiency microwave heating methods

Under the condition that the microwave frequency (f) was held constant, the increase in electric field strength (E), relative permittivity (k'), and loss tangent ($\tan\delta$) increased the absorbed power per unit volume. Thus, the increase of

Table 1 The primary chemical composition of lunar regolith returned by sampling

Sample composition	Apollo						Luna		CE	
	11	12	14	15	16	17	16	20	5	6
SiO_2	42.20	46.17	48.10	46.20	45.09	39.87	43.96	44.95	42.20	45.60
TiO_2	7.80	3.07	1.70	2.16	0.56	9.42	3.53	0.49	5.00	2.70
Al_2O_3	13.60	13.71	17.40	10.32	27.18	10.97	15.51	23.07	10.80	14.30
FeO	15.30	15.41	10.40	19.75	5.18	17.53	16.41	7.35	22.50	17.30
Fe_2O_3	—	—	—	—	—	—	—	—	—	—
MgO	7.80	9.91	9.40	11.29	5.84	9.62	8.79	9.26	6.48	7.08
CaO	11.90	10.55	10.70	9.74	15.79	10.62	12.07	14.07	11.00	11.90
Cr_2O_3	0.30	0.35	0.23	0.53	0.11	0.46	0.29	0.15	—	—
Na_2O	0.47	0.48	0.70	0.31	0.47	0.35	0.36	0.35	0.26	0.25
K_2O	0.16	0.27	0.55	0.10	0.11	0.08	0.10	0.08	0.19	0.07
MnO	0.20	0.22	0.14	0.25	0.07	0.24	0.21	0.11	0.28	0.22
P_2O_5	0.05	0.10	0.51	0.06	0.06	0.13	0.21	0.08	0.23	0.07
Total	99.78	—	99.83	—	—	99.29	—	99.96	98.94	99.42

microwave heating effect was achieved. Three approaches were proposed in this study to improve the microwave heating effect (as shown in Fig. 2). These approaches included increasing electric field strength, delimiting microwave heating temperature range, and enriching high-loss lunar regolith minerals. Under the lunar environment, the collected lunar regolith minerals were first sorted according to their dielectric properties. High-loss minerals were heated by microwave, while low-loss minerals were heated by conventional methods. In addition, a combined heating method was adopted. Within the temperature range where minerals transformed into microwave absorbers, microwave heating was employed. In other temperature ranges, conventional methods were utilized. According to Pei et al. (2024)'s classification of ISRU phases, the application of the three highly efficient microwave heating methods were concentrated in the mineral extraction phase.

2.2.1 Increasing the electric field strength

The electric field strength of microwaves could be increased by increasing microwave power and modifying waveguide structure. The increase in transmission power required a higher-power microwave power supply and additional energy input. It was not suitable for the lunar surface construction environment. Therefore, to achieve efficient microwave heating, a method for enhancing electric field strength based on a compressed waveguide was proposed in this study to improve microwave heating efficiency. As a variant of the rectangular waveguide, the compressed waveguide could effectively increase the electric field strength. It works by compressing the physical dimensions of the rectangular waveguide to focus and increase the electric field. Microwaves entered the input port of the compressed waveguide. As the waveguide deforms, this deformation induces microwave end-face cutoff at the output end, thereby increasing the electric field strength. The compressed waveguide has a simple structure, with relatively low processing difficulty and production cost. It is expected to be applied to ISRU.

To analyze the electric field enhancement effect of the compressed waveguide, a solid model was created in COMSOL based on its geometric dimensions. This model represented only the internal structure of the compressed waveguide. Simultaneously, a solid model of a conventional resonant cavity with the same initial cross-sectional geometry as the compressed waveguide was constructed. In the Electromagnetic Fields module, a rectangular waveguide excitation was applied at a frequency of 2.45 GHz and an input power of 100 W. The electric field distributions for both the compressed waveguide and the conventional resonant cavity were obtained using a frequency-domain solution, as shown in Fig. 3.

As shown in Fig. 3, under identical power and frequency conditions, the electric field intensity within a resonant cavity of the same dimensions as the compressed waveguide exhibits a TE10 mode distribution. This distribution was characterized by multiple regions of concentrated electric field strength, with a maximum intensity of 1.13×10^4 V/m. The electric field distribution within the compressed waveguide is more concentrated, exhibiting a single peak with a maximum electric field intensity of 1.73×10^4 V/m—representing an increase of approximately 53% compared with that in the

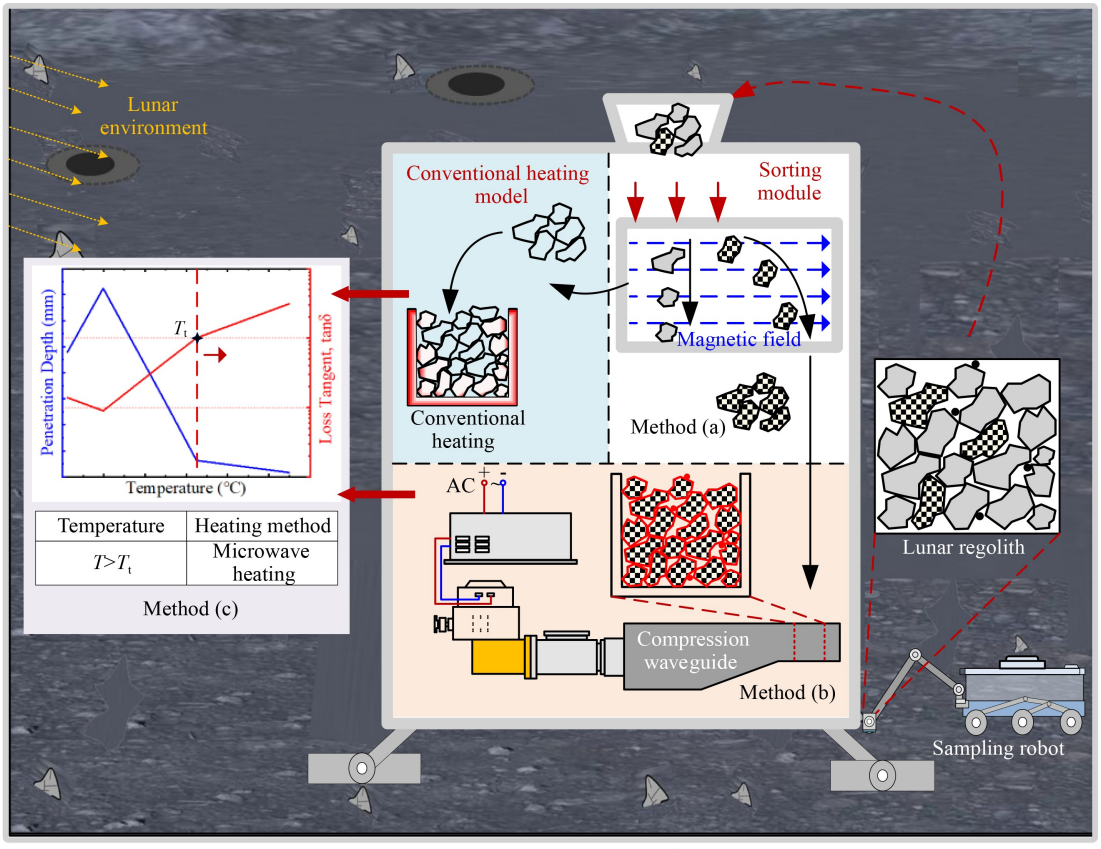
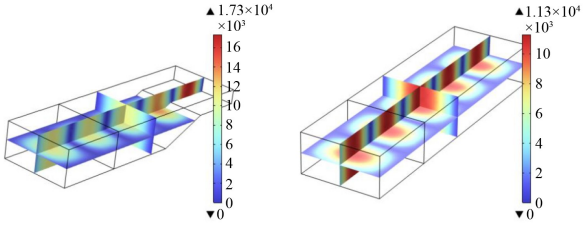


Fig. 2 High-efficiency microwave heating method.



(a) Compression waveguide (b) Conventional resonators

Fig. 3 Electric field distribution in compressed waveguides and conventional resonators.

conventional resonant cavity. Therefore, under identical input power and frequency conditions, the predicted heating rate of the compressed waveguide is approximately 1.5 times that of the conventional resonant cavity.

2.2.2 Delimiting the heating temperature range

Lunar regolith was found to be a low-loss material at low temperatures and a high-loss material at high temperatures. The temperature point (T_t) with a loss tangent (tanδ) of 0.1 was defined as the dielectric property transition temperature point of lunar regolith. The heating temperature was divided into low-temperature and high-temperature ranges based on whether the loss tangent (tanδ) was greater than 0.1 (as shown in Fig. 4). Specifically, the temperature range with a loss tangent (tanδ) greater than 0.1 was designated as the high-temperature range, and the range with a loss tangent (tanδ) below 0.1 was designated the low-temperature range. Thus, a composite energy field heating method was proposed in this study to achieve the high-efficiency heating of lunar regolith. Specifically, microwave heating was adopted in the high-temperature range where microwave has a good coupling effect with lunar regolith. In the low-temperature range, induction heating, solar heating, laser heating, or resistance heating are employed. Efficient and low-consumption heating of lunar regolith is achieved through multiple heating methods to better support the *in situ* utilization of lunar surface resources.

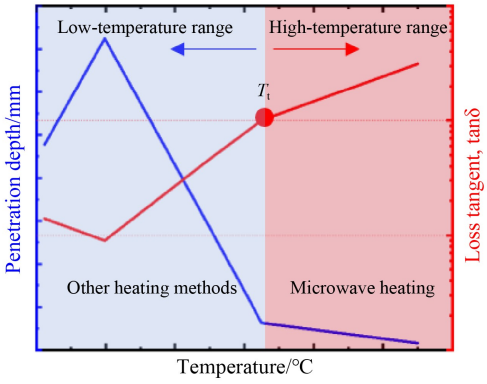


Fig. 4 Delimiting the heating temperature range.

At the same frequency, the penetration depth (D_p) and loss tangent (tanδ) of different types of lunar regolith simulants exhibited the same variation trend with temperature. However, due to the different mineral compositions of the lunar regolith simulants, the temperature for their transformation from microwave transparents to microwave absorbers varied (Allan et al., 2013; Kim et al., 2024). Based on this characteristic, the determination of the transition temperature point was required in accordance with the type of lunar regolith in the ISRU. The objective was to identify the temperature range suitable for microwave heating.

2.2.3 Enriching high-loss lunar regolith minerals

The degrees of interaction between different minerals in lunar regolith and microwaves were found to be different. Better heating effects were exhibited by ilmenite in a microwave field (Kim et al., 2024). Therefore, when microwave is used as the heating method for the ISRU, priority could be given to the sorting and enrichment of high-loss minerals in lunar regolith. Compared to unsorted lunar regolith, sorted ilmenite exhibits superior heating efficiency in a microwave field, thereby enhancing microwave heating efficiency. Other minerals were heated in conventional heating methods (Fig. 5).

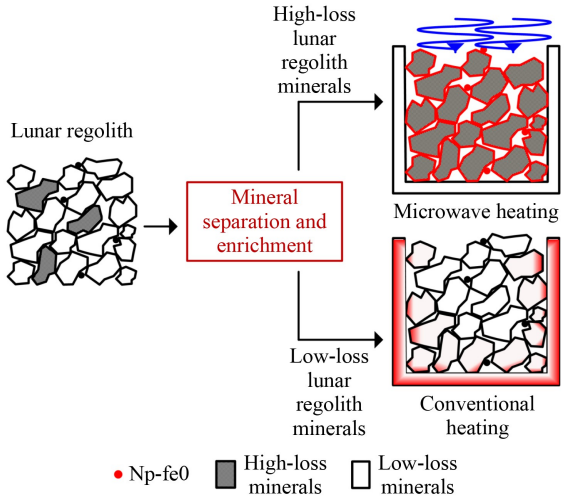


Fig. 5 Enriching high-loss lunar regolith minerals.

3 Experimental validation of increased electric field intensity

3.1 System construction

To verify the effect of increased electric field strength on efficient microwave heating, a high-efficiency microwave heating test system was designed in this study based on the structure of the compressed waveguide.

The high-efficiency microwave heating system for lunar regolith consisted of a power supply unit, a cooling unit, a microwave heating unit, and an electronic control unit. Energy was supplied to the other three units by the power supply unit. The cooling unit was connected to the magnetron, circulator, and water load of the microwave heating unit via rubber hoses. Its purpose was to reduce the overall temperature of the device and avoid damage caused by high temperatures. The electronic control unit mainly included a microwave power supply, a power control panel, and a computer. It was used to control the microwave output power and collect data. As the core unit of this system, the structural composition and basic functions of each part of the microwave heating unit were as follows.

1) The operating frequency of the magnetron was 2.45 GHz, and its maximum output power was 1500 W. It was used in conjunction with the microwave power supply and power control panel of the electronic control unit. The microwave power supply was an air-cooled type, which could adjust power in real time. Its maximum supported input power was 2000 W. The output power of the microwave power supply could be adjusted between 300 W and 1500 W via the power control panel.

2) The circulator and water load were connected to the microwave source via flanges. Microwaves were transmitted directionally during operation, thereby reducing damage to the magnetron caused by microwave reflection.

3) The main structure of the heating cavity was a compressed waveguide, which was used in conjunction with alumina fiber insulation boards and a crucible. The compressed waveguide was connected to the microwave transmission unit via flanges. It generated a concentrated electric field for heating the lunar regolith simulant. The alumina fiber insulation boards were used to reduce

thermal convection and improve heating efficiency. The crucible was used to hold the lunar regolith simulants. The diameter (d) of the electric field concentration area of the system was 30 mm, and the height (h) was 20.2 mm.

4) Thermocouple was used to measure the temperature inside the heating cavity. It was used in conjunction with the electronic control box and computer of the electronic control system. Experimental data were stored in the computer via the electronic control box. The temperature rise rate of the system and the state of the lunar regolith simulant could be judged based on the real-time displayed data.

The assembled high-efficiency microwave heating system was shown in Fig. 6.

3.2 Material and heating process

The utilization of lunar materials is one of the primary methods for ISRU on the lunar surface. Among these, lunar ilmenite serves as the main source of iron and titanium metals, and its reduction provides the foundation for obtaining life support materials on the lunar (Liu et al., 2022). Due to limitations in lunar regolith availability, this study employed the national standard sample CLRS-2 (high-titanium lunar regolith simulant) provided by the Institute of Geochemistry, Chinese Academy of Sciences. As a national standard sample, it exhibits chemical composition similar to lunar regolith, as shown in Table 2.

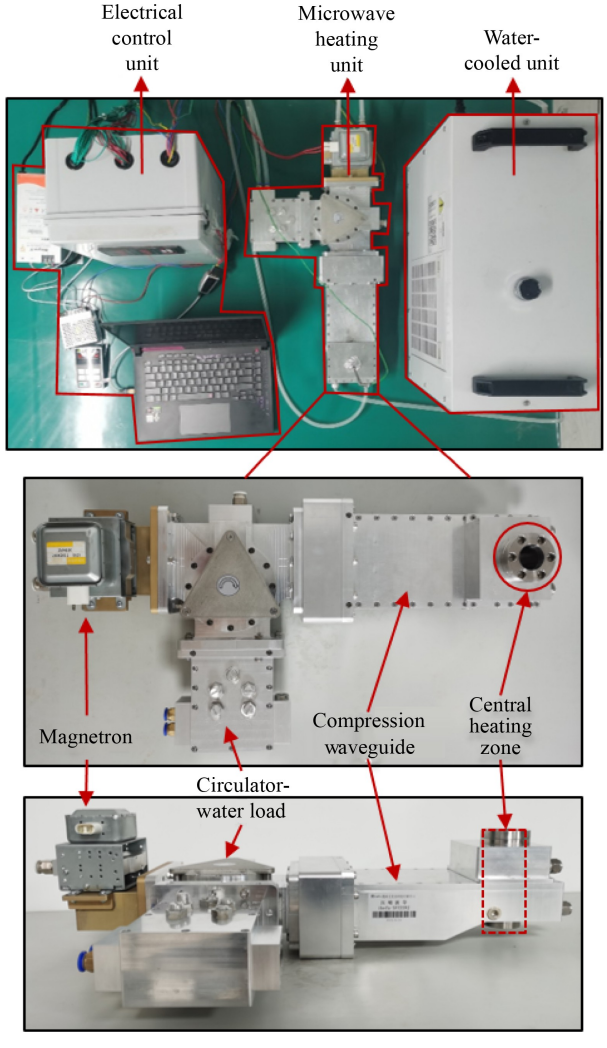


Fig. 6 High-efficiency microwave heating system.

To achieve the microwave self-heating process of lunar regolith simulants, SiC was not used as a susceptor for auxiliary heating in the experiment. Only the microwave absorption capacity of lunar regolith simulants was utilized for self-heating. The basic layout of the microwave heating system was shown in Fig. 7. Microwave energy was provided by a magnetron with adjustable input power. The inner lining of the compressed waveguide was made of alumina fiber boards for heat insulation and preservation. CLRS-2 lunar regolith simulant was loaded into an Al_2O_3 crucible. The crucible was placed at the position with highly concentrated electric field inside the compressed waveguide. To avoid the failure of the thermocouple in the high-frequency electromagnetic field and the impact on the microwave self-heating effect. A thermocouple was inserted at the alumina fiber board to measure the temperature of the air inside the cavity. The air temperature inside the cavity remained lower than both the surface and interior temperatures of the lunar regolith simulant throughout the microwave heating process (Allan et al., 2013). Therefore, the temperature of the CLRS-2 during the experiment was higher than that measured by the thermocouple. Heating was carried out under normal temperature and pressure, with input powers of 300 W, 400 W, 500 W, and 800 W. When the target heating time or temperature was reached, the microwave power supply was turned off. The lunar regolith simulant sample was allowed to cool naturally to a safe temperature for removal from the heating system.

3.3 Results

The temperature rise rate of the gas inside the compressed waveguide under different powers was shown in Fig. 8. Based on whether thermal runaway occurred, the microwave heating powers were divided into low powers (300 W and 400 W) and high powers (500 W and 800 W). When the microwave input power exceeded 500 W, CLRS-2 lunar regolith simulant still exhibited a fast temperature rise rate without SiC assistance. Thermal runaway was observed in this case. With the increase in

Table 2 Chemical composition of lunar regolith simulant CLRS-2 (Zhang et al., 2024)

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	TiO_2
Contents/wt.%	40.73	12.33	18.04	7.55	10.25	2.42	0.77	0.20	0.16	6.58

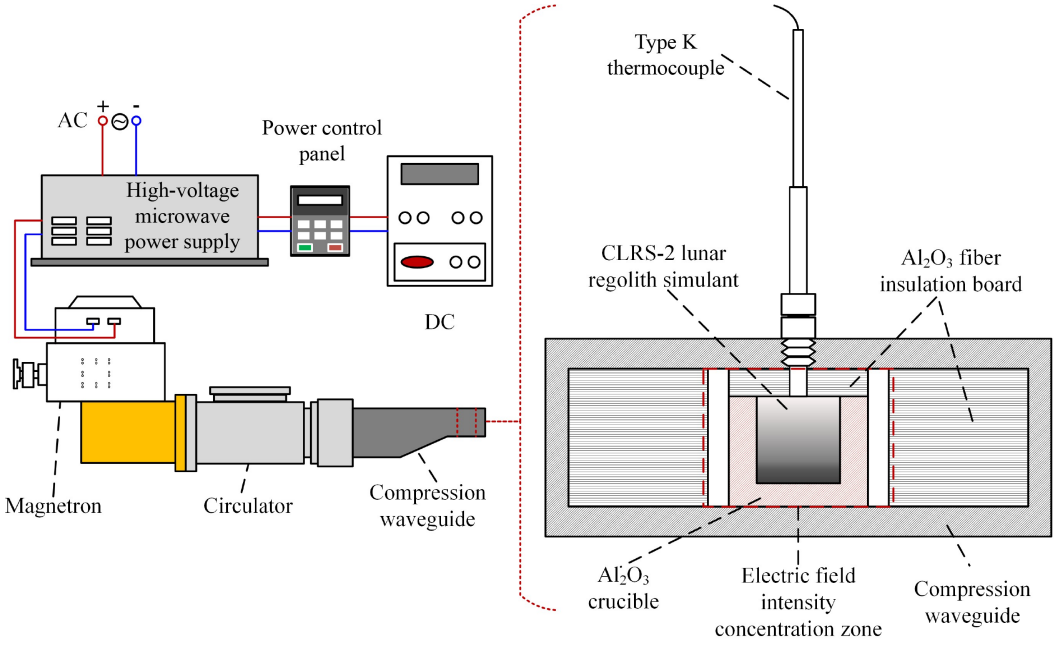


Fig. 7 Scheme of the heating system setup.

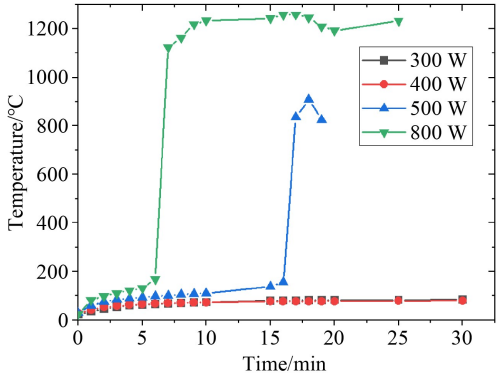


Fig. 8 Temperature in microwave heating.

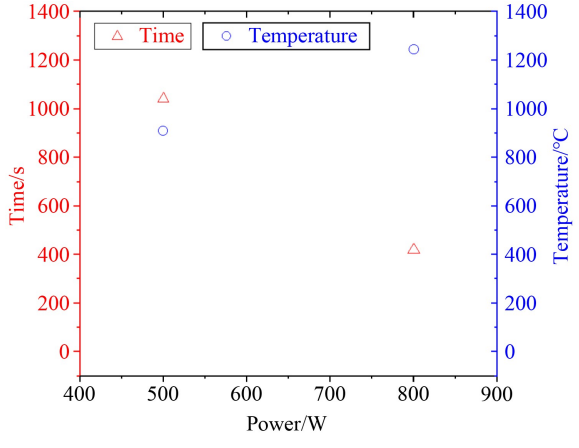
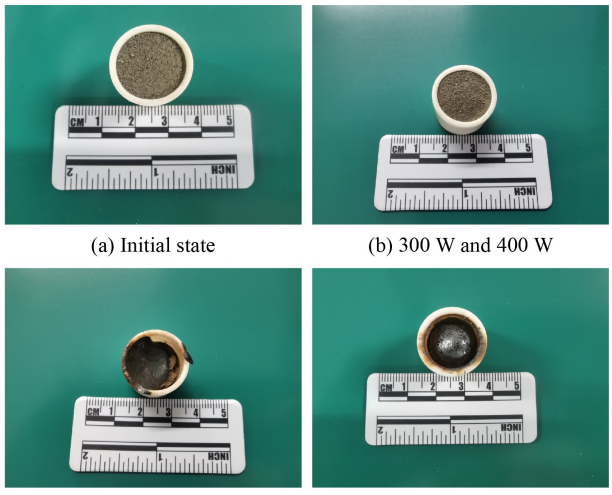


Fig. 9 Thermal runaway time and temperature.

heating power, the occurrence time of thermal runaway was advanced and the achieved temperature was higher, as shown in Fig. 9. It could be seen from the figure that when the microwave power was increased from 500 W to 800 W, the occurrence time of thermal runaway was advanced from 1043 s to 420 s. The temperature of thermal runaway was increased from 909.7°C to 1259°C.

The increase in temperature enhanced the dielectric properties of the lunar regolith simulants. Thereby, the interaction effect between microwaves and the material was improved (Huang and Lu, 2009). Hence, thermal runaway was a positive feedback result of the interaction between microwaves and the material. It was beneficial to achieving the rapid temperature rise of the lunar regolith simulants.

Figure 10 showed the appearance characteristics of the samples before and after microwave heating (300, 400, 500, and 800 W microwave powers). At low powers, the loss tangent (tanδ) of the lunar regolith simulant was small. Less microwave energy was converted into thermal energy. Meanwhile, a large amount of convective heat dissipation was generated during the microwave self-



(a) Initial state (b) 300 W and 400 W

(c) 500 W (d) 800 W

Fig. 10 Sintered samples at 300, 400, 500 and 800 W.

heating experiments under normal temperature and pressure. These factors led to a low temperature in low-power microwave heating. Thus, no significant changes occurred in the lunar regolith simulant. At high powers, the lunar regolith simulant was sintered. At a power of 500 W, thermal runaway occurred, and heating was subsequently stopped, leading to the sample not being fully sintered. The sintered samples exhibited a black color. This color was different from that of the lunar regolith simulant powder. It was speculated that an oxidation reaction took place between the minerals and air during the heating process.

Compared with microwave self-heating using the CPI Autowave system and ordinary microwave equipment, a faster temperature rise rate could be achieved at lower power by using a compressed waveguide, as shown in Fig. 11. The figure presented the temperature change curves of JSC-1AC heated by the CPI Autowave system at 3000 W, KLS-1 heated by an ordinary microwave equipment at 1000 W, and CLRS-2 heated by the proposed system at 800 W, respectively. It could be seen from the figure that after the electric field strength was increased by the compressed waveguide, the effect of microwave self-heating was significantly improved. At a microwave power of 800 W, thermal runaway of CLRS-2

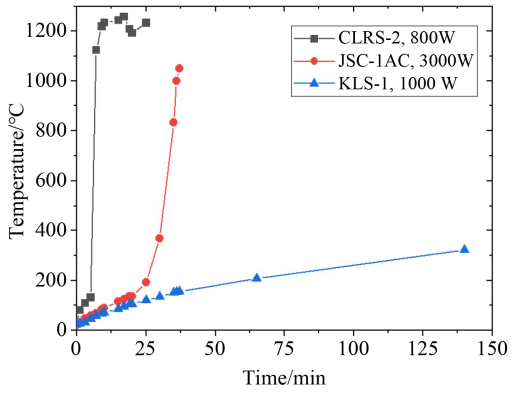


Fig. 11 Microwave self-heating effect (Allan et al., 2013; Kim et al., 2024).

lunar regolith simulant occurred at 7 min, with the maximum temperature reaching 1259°C. Compared with the CPI Autowave system, its thermal runaway time was advanced by approximately 30 min and the temperature was increased by about 200°C. Since the mass and chemical composition of lunar regolith simulants varied among different studies, as shown in Table 3, the comparison of heating effects was only a preliminary judgment. Quantitative evaluation with controlled variables would be required in subsequent studies.

4 Conclusions

The principle of microwave heating lunar regolith was analyzed, and the unique advantages of microwave heating for lunar regolith were identified in this study. Based on the temperature-dependent variation of the macroscopic dielectric properties of lunar regolith simulant and its mineral composition, three high-efficiency microwave heating methods oriented to the ISRU were proposed. These methods included increasing electric field strength, delimiting microwave heating temperature range, and enriching high-loss lunar regolith minerals. A high-efficiency microwave heating system based on a compressed waveguide was designed. It can realize the enhancement of electric field strength and efficient microwave heating. This study provided new

Table 3 Chemical composition and mass of lunar regolith simulant CLRS-2, JSC-1AC, and KLS-1 (Allan et al., 2013; Hill et al., 2007; Kim et al., 2024; Zhang et al., 2024)

LRS	Mass (g)	Chemical composition (wt%)									
		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	TiO_2
CLRS-2	7.4	40.73	12.33	18.04	7.55	10.25	2.42	0.77	0.20	0.16	6.58
JSC-1AC	40	46.2	17.1	—	6.87	9.43	3.33	0.85	0.19	0.62	1.85
KLS-1	17	48.0	15.3	4.75	9.64	8.38	3.42	1.52	0.17	0.33	1.67

references for the application of microwaves in the ISRU. The main conclusions are summarized as follows.

1) Three high-efficiency microwave heating methods were proposed, which included using a compressed waveguide to replace resonant cavity to increase electric field strength (electric field strength is increased by approximately 53%), delimiting microwave heating temperature range (microwave heating is employed when tanδ > 0.1), and enriching high-loss lunar regolith minerals (such as ilmenite).

2) A high-efficiency microwave heating system based on a compressed waveguide was designed. Microwave self-heating experiments were conducted using this system. When the microwave power exceeded 500 W, thermal runaway occurred during the heating process. With the increase in microwave power, the occurrence time of thermal runaway was advanced and the thermal runaway temperature was increased. At a power of 800 W, thermal runaway of the lunar regolith simulant occurred at 420 s, with the maximum temperature reaching 1259°C. Compared with other heating systems, this system exhibits better microwave heating performance.

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Declaration of competing interest

Authors declare that they have no competing interests.

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