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Water extraction from icy lunar simulants using low power microwave heating

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ABSTRACT

Identifying the best technique for extracting water ice deposits in permanently shadowed regions at the lunar poles will be crucial in determining how successful a long-term or permanent settlement at these locations will be for future scientific and technology missions. This study uses a low-power microwave heating method to extract water from icy lunar simulants. Samples of lunar highland and mare simulants at different water contents (3–15 wt %) were heated using 250 W, 2.45 GHz microwaves. A maximum of 67 ± 5% [2SD] of the water was extracted during heating runs of 25 min. Water was extracted more efficiently from the highland simulant than from the mare simulant. A significant reason for the different efficiency of water extraction in icy lunar simulants was the differing porosity of the samples made from different simulants. Pore space filled with ice leads to a reduced contact area between grains and an increased area of free ice, which causes poor heating performance. The results indicated that differences in chemical composition between the simulants had a negligible effect on water extraction, as the contact area between grains seems to dominate water extraction. This study found that low-power microwave heating is an effective technique for extracting water from cryogenic icy simulants. It was also found that using a simple input energy principle (Input Energy = Absorbed Power x Heating Time) to estimate the additional heating time was sufficient to overcome inefficient heating due to differing absorbed powers. For undersaturated samples, microwave heating was an efficient heating mechanism, but is less efficient for saturated samples where alternative heating methods may be more efficient at melting free ice before employing microwave heating.

1. Introduction

Recent discoveries that Permanently Shadowed Regions (PSRs) at the poles of the Moon host concentrated deposits of water ice significantly increase the possibility of a sustained human presence on the lunar surface in the near future. Due to no direct exposure to sunlight, PSRs reach extremely cold temperatures, with many being in the temperature range required for water ice to be stable over geologic timescales (<110 K) [1,2]. The Lunar Crater Observation and Sensing Satellite (LCROSS) mission [3] enabled the only in situ measurement of lunar water to date, measuring a water ice content of 5.6 ± 2.9 wt % [1SD] from an ejecta plume expelled from the PSR within the Cabeus crater. The data from various scientific instruments onboard the Lunar Reconnaissance Orbiter (LRO) have provided evidence that ice is present in PSRs in a low to medium concentration (1–10 wt %) with a frost-like form on the surface. Radar data from LRO has suggested that ice could exist in much larger quantities than mere frost would account for [4,5]. Up to 30 wt % deposits have been speculated to exist in PSRs as granular solid ice mixed in with, but separate from, the regolith [6]. Water ice is a promising resource as it could be harvested and used to sustain human habitation through drinking water, agriculture, and other life-supporting activities. Possibly, more importantly, the water can be electrolysed into O2 and H2, which can be used in propulsion systems as fuel. The ability of water to be used as a propellant makes this resource a specific focus for a sustainable economic ISRU system in cislunar space [7,8].

Microwave heating is a technique that could efficiently extract ice from PSRs as the process heats the bulk of a medium [9–11]. Compared to conventional heating methods that predominantly rely on conductive and convective heat transfer from external heat sources, microwave heating...
energy excites the polar molecules in materials as they try to align with the applied electric field. This excitation generates heat due to the resulting friction among the excited molecules. Therefore, microwave energy can uniformly heat materials throughout their entire volume. Microwave heating has many uses in industry [12-15] and has been recognised as an efficient heater of lunar simulates in lab experiments [16] and simulations [17]. Microwave heating is considered a more viable fabrication method for a 3D printing platform compared with solar and laser sintering, as this technique does not depend on the availability of sunlight and only requires ~23% of the energy compared to that for laser sintering with reduced fabrication time, due to the volumetric heating that is intrinsic to the process [16,18]. Previous studies investigated water ice extraction from lunar simulants using microwave heating and found that high efficiencies of water extraction are possible from -50 °C samples with a low water content (1–2 wt %) [10,11]. These studies, however, concentrated on high-power microwave (1-1.2 kW). Using lower-power microwaves would make an initial mission to a PSR more feasible using the expected energy constraints imposed by a lander or rover platform. If the efficacy of the process can be understood and the yield quantified on a small-scale basis using lower-power heating, the water ice content of the site can be calculated and used to confirm the site’s candidacy for a full-scale mining campaign (requiring up to 2450 MT per year [8]). Investigating the interaction of microwaves with complex icy regolith matrix samples at low power could prove a vital step in establishing the validity of microwave heating as a technique for prospecting and extracting water ice at the lunar surface.

In this study, two lunar regolith simulants containing different water contents, guided by the LROSS results (3, 6, 9, 12, 15 wt %) were prepared. The samples were each heated for 25 min using 250 W, 2.45 GHz microwaves. The water extraction during heating was investigated to guide how future microwave heating instruments could be developed into lunar payloads and prospecting suites. Of particular interest to this study is how material properties such as porosity, bulk composition, and water content alter the process of water extraction during microwave heating.

2. Method

2.1. Simulants

Two simulants were used for this study: LHS-1 and LMS-1, chosen to mimic the lunar highlands and lunar mare material, respectively [19,20]. Both simulants are produced by CLASS Exolith Lab. Exolith creates its simulants by mixing mineral and polymineralic grains to accurately represent the grain size and composition of lunar material. Like most simulants in production, neither simulant contains agglutinates or nanophase iron (np-Fe\textsuperscript{0}), with np-Fe\textsuperscript{0} being of particular interest in microwave heating studies. Research has indicated that np-Fe\textsuperscript{0} in real lunar regolith could act as energy sinks for microwave energy, making the heating more effective and leading to higher yields [9].

LHS-1 is a lunar highland simulant representing an average highland location on the Moon based on the data from the Apollo highland soils [19]. LHS-1 has a mean particle size of 90 μm with a size range of 0.04–1000 μm, a grain density of 3.22 g/cm\textsuperscript{3} and a porosity of 59.6% [21]. LMS-1 is a lunar mare simulant made to represent an average mare location on the Moon based on Apollo mare soils [20]. LMS-1 has a mean particle size of 91 μm with a size range of 0.04–1000 μm, a grain density of 3.03 g/cm\textsuperscript{3} and a porosity of 48.5% [21]. These values are within the expected range for lunar samples [22]. The bulk oxide composition of the two simulants selected along with other commonly used simulants NU-LHT-2M, JSC-1A and Apollo samples from both mare and highland regions [23-25] can be found in Table 1. Previous simulations have shown that the overall microwave heating performance due to differences in TiO\textsubscript{2} content is negligible as it does not have a major effect on the dielectric properties of the simulants. Therefore other oxide contents are of more interest in this study [17]. Laboratory experiments have shown mare simulants couple to microwaves more efficiently than highland simulants showing quicker temperature increases and more dramatic thermal runaway with current theories linking this difference to Fe content [16]. Understanding how oxide content differences affect the subsequent water extraction in icy regolith is currently not fully understood and is important to this investigation. Any difference in water extraction due to differences in silicon composition would be expected to be seen in every sample independent of the water content of the sample.

2.2. Sample preparation

The majority of water ice present at the lunar poles is thought to have been delivered through various impacts and deposition events and not through the classical heating, melting and precipitation cycles that occur on the Earth [26]. In this study, samples were prepared using a feasible plan that would allow multiple samples to be prepared in a reasonable time frame. To this end, samples were created using the commonly used "mud-pie" technique [27], where deionised water (12.5 MΩ cm) was added by a syringe to a polythene bag filled with approximately 120 g of desiccated simulant to the required water content (3–15 wt %). The bag was taped shut, manipulated by hand to distribute the water, and left for 12 h to allow even distribution of water. The bag is weighed at this point to determine the water content of the sample. No water content difference is shown over the 12 h. The simulant was deposited into alumina crucibles with dimensions of 52 mm × 50 mm (See Fig. 1). The inside of the crucible was wrapped with 2 mm thick ceramic paper to reduce thermal shock and to prevent the sample from fusing to the crucible during heating. The ceramic crucible and ceramic paper are transparent to microwave energy. Approximately 40 g of wetted simulant was added to each crucible and then compressed with a force of 1 N. The crucibles were added to a sealed cryo-cooler, whereupon N\textsubscript{2} gas at 90 K was passed over the samples until a control sample reached an internal core temperature of 100 K. Using N\textsubscript{2} as the cooling gas in a sealed environment ensured water absorption onto the samples was negligible.

An LHS-1 sample with 6 wt % of water content is shown in Fig. 1. The bulk densities of compressed samples at 100 K are shown in Fig. 2, with the error bars being calculated using the propagation of errors from sources of random error. Systematic errors from measuring the crucible dimensions were approximately 4%. LMS-1 samples had higher densities than respective LHS-1 samples at each equivalent water content. This was presumably due to the lower porosity of LMS-1. A 15 wt % LMS-1 sample was not used for experiments due to being beyond the
saturation point, as liquid water was visible on the surface of the simulant at this water content.

2.3. Microwave heating unit (MHU)

The MHU is a bespoke industrial unit capable of producing 200–1000 W microwaves at 2.45 GHz into a 110 mm diameter cylindrical cavity. The MHU cavity can be pumped down to a pressure of 5 mbar using a scroll pump and down further to 10⁻⁵ mbar using a turbomolecular pump. The surface temperature of the sample is determined by two pyrometers with temperature ranges of 0–500 °C and 500–1400 °C. The sample can be viewed during heating via a viewport. The full MHU setup is described further in Lim et al. [16]. The specific setup used in these experiments is shown in Fig. 3. In these experiments, the scroll pump was kept constantly pumping on the cavity to ensure all the water vapour could be released. The turbomolecular pump was not used. A pressure sensor was connected between the cavity and the scroll pump. As the scroll pump was constantly pumping on the cavity, the pressure measurements can be used to indicate rising water vapour levels but cannot be used to calculate the yield. During operation, a hotspot occurs in the MHU where the local electric field in the sample is at its maximum. Samples were placed in the cavity on top of alumina supports, allowing the sample to be placed in the hotspot at a height of ~5 cm. The hotspot location is different for different materials as the resonant frequency changes but can be adjusted by changing the vertical tuner settings. The side tuners are used to minimise the reflected power. Both vertical and side tuners are used to ensure microwave absorption into the sample is maximised. The tuner settings, called microwave settings from here on, need to be modified for each material to ensure maximum heating performance. The optimum microwave settings for each simulant are found by doing control runs and adjusting the settings until the reflected power is minimised as much as possible. The settings were kept the same for each simulant set.

2.4. Heating method

Once the sample in the cryo-cooler had cooled to 100 K, the sample’s frozen mass was measured, and it was placed in the MHU cavity. The door was closed, and pump-down began. The MHU cavity has no active cooling stage to keep cryogenic samples cool before heating. The ceramic paper in the crucible acts as an insulator to passively keep the sample cool. The microwave energy was turned on when the pressure was below 5 mbar. The time taken to remove the sample from the cryo-cooler, place it in the cavity and evacuate to below 5 mbar was typically 5 min. Control samples placed on a bench reached a temperature no higher than 130 K in 10 min. After heating for the allotted time, the sample was removed, and the post-MHU mass was measured. The sample was then placed in a 200 °C vacuum oven for 12 h to remove any remaining water. The drying time was determined using control samples where 99% of doped water was removed in less than 12 h. After removal from the vacuum oven, the desiccated mass of the sample was measured. Initially, a heating time of 35 min was decided upon using previous results [28]; however, almost all the water was extracted so two further tests were conducted at 20 and 25 min to find a point at which roughly 50% of the water was being removed. This extraction ratio was decided upon so that differences between the two simulant sets could be easily detected.

![Fig. 1. Left) A side-on picture of a crucible with dimensions. Right) An LHS-1 sample at 6 wt % water content. The sample is placed in an alumina crucible lined with ceramic paper to protect the crucible from thermal shock and prevent the sample fuses into the crucible. The sample has an internal temperature of 100 K when in the sample cooler.](image1)

![Fig. 2. Bulk densities of all samples used in this study compressed with 1 N of force and frozen to 100 K. Densities of dry values are higher than those quoted in Refs. [19,20] due to compression. Error bars represent 2-sigma random errors. Systematic errors were found to be approximately 4%.](image2)
comparable. For LHS-1 (6 wt% water), approximately 40% of water was removed in 20 min, while 60% was removed in 25 min and 88% in 35 min. Therefore, 25-min heating runs were used for the full set of experiments.

3. Results

Three runs at specific water contents (between 3 and 15 wt %) using both simulants were completed, using 250 W microwaves. During the microwave heating, plasmas would form in the cavity as gases were expelled from the sample and interacted with the microwaves. The gases present could be estimated through spectral identification. The significant gases present during any run were determined to be H (pink), O (violet), N (bright blue/white), and H$_2$O (purple/blue). Any present hydrogen and oxygen are likely to be sourced from the dissociation of H$_2$O \cite{29}. Pictures of an example 25-min run at various stages are shown in Fig. 4.

Fig. 4a shows the sample on the ceramic support during pump-down. Fig. 4b shows the sample as the microwaves are first turned on. The bright plasma is thought to be any excess N\textsubscript{2} from the cooling process being driven off. Fig. 4c shows the sample after 15 min of heating. The plasma is water vapour being released from the sample. The average water extraction of these three runs for each water content and simulant combination is shown in Fig. 5 with the results summarised in Table 2.

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![Fig. 4. An example heating run of an LHS-1 6 wt % sample. a) before heating, b) at 5 min, with a bright white plasma from N\textsubscript{2} and, c) at 15 min with a purple plasma of released water vapour.](image-url)
was also measured to ensure any simulant mass loss during microwave heating experiment was performed for 5 min longer (totalling 30 min) with the 6 wt % LMS-1 sample, which would result in the same total power of 57 W. This means the average power absorbed into the sample less optimal, but still satisfactory settings, with an average reflected power of 28 W, indicating lunar mare pressure of 10.7 mbar with a clear peak at 25 min. The temperature of the samples was measured every 5 min using the pyrometers (Fig. 7). In general, the temperatures of all LHS-1 samples reached higher temperatures than LMS-1 samples. For LHS-1 samples, a trend is seen in that the lower the water content of the samples, the higher the peak temperature at 25 min. Such a trend was not seen for LMS-1 samples. Much lower gaps are seen between the final temperatures of different water content LMS-1 samples.

4. Discussion

This study has confirmed previous results in that extracting water from cryogenic icy simulants is possible [10,11]. Up to 67% and 55% of the water can be extracted within 25 min of heating at 250 W input power (equivalent to 375 kJ of energy input) in LHS-1 and LMS-1 samples, respectively. This study shows that water extraction is possible at lower sample temperatures and power settings than previously investigated. The main difference between the two simulants is their respective Fe oxide composition. It is known that Fe has a considerable effect on microwave absorption, evidenced by lunar mare

Table 2
A summary of the extraction results. Average values are provided.

<table>
<thead>
<tr>
<th>Simulant Type</th>
<th>Water Content (wt. %)</th>
<th>Initial Water Mass (g)</th>
<th>Extracted Water (g)</th>
<th>Extraction Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHS-1</td>
<td>3.0</td>
<td>1.2</td>
<td>0.8</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>5.6</td>
<td>2.3</td>
<td>1.5</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>9.2</td>
<td>3.7</td>
<td>2.4</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>12.2</td>
<td>5.0</td>
<td>3.3</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>14.7</td>
<td>6.0</td>
<td>2.9</td>
<td>68</td>
</tr>
<tr>
<td>LMS-1</td>
<td>3.1</td>
<td>1.2</td>
<td>0.6</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>2.6</td>
<td>1.3</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>9.6</td>
<td>3.8</td>
<td>2.1</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>12.5</td>
<td>5.1</td>
<td>1.6</td>
<td>32</td>
</tr>
<tr>
<td>LMS-1 (30 min)</td>
<td>6.3</td>
<td>2.5</td>
<td>1.7</td>
<td>69</td>
</tr>
</tbody>
</table>

Fig. 5. Extracted water mass against water content for different samples. Water content is displayed as weight percentage in the bottom x-axis and as a mass content in the top x-axis. Extracted water mass is calculated by subtracting microwave heating mass from the final desiccation mass. The water extracted data shows LHS-1 25-min runs (red), LMS-1 25-min runs (blue), and LMS-1 30-min run (black). Solid lines show linear regression, respective to colour with r² > 0.98 for both simulants (unavailable for a single datapoint, LMS-1 30-min run). Shaded areas are 1-sigma from the regression line. Dashed lines indicate a change in the trend when the water content is raised to a certain percentage for each simulant type.

The mass of water in the sample before and after the heating run was used to calculate the mass of water extracted. The final desiccated mass was also measured to ensure any simulant mass loss during microwave heating could be accounted for. The mass of water extracted increases with increased water content for both simulants. Upwards of 67 ± 5% and 57 ± 4% of the water was extracted from LHS-1 and LMS-1 samples respectively. However, for LHS-1 at 12 wt % and LMS-1 at 15 wt %, the extracted water decreases to 48 ± 2% and 32 ± 1% respectively. This suggests that there is an upper limit of water concentration, after which the rate of extraction starts to decrease.

LHS-1 samples had an average reflected power of 28 W, indicating the microwave settings were close to optimum. In contrast, LMS-1 had less optimal, but still satisfactory settings, with an average reflected power of 57 W. This means the average power absorbed into the sample was 222 W and 193 W for LHS-1 and LMS-1 respectively, with the input power of 250 W being kept the same for both samples. An additional heating experiment was performed for 5 min longer (totalling 30 min) with the 6 wt % LMS-1 sample, which would result in the same total amount of absorbed power (222 W) as the equivalent LHS-1 samples. The extra 5 min of heating was calculated using energy input principles (Energy Input = Absorbed Power x Heating Time). The 30-min runs had a water extraction mass similar to the equivalent 25-min run for LHS-1. The 30-min runs are also shown in Fig. 5.

The MHU cavity pressure was measured every 5 min during a heating run. The average pressure of each set of runs for a respective water content is shown in Fig. 6. The top figure of Fig. 6 shows the LHS-1 averages, while the bottom figure shows the LMS-1 averages. As this is an open system, the pressure can be used to show trends but cannot be used to calculate volumes and quantities of released gases. As expected, the higher water content samples resulted in higher peak pressures. Peak pressures were reached for all the LHS-1 samples up to 12 wt % within 25 min, but a peak pressure was only reached for the 9 wt % LMS-1 sample. The highest water content samples, the 12 wt % LMS-1 and 15 wt % LHS-1 samples, had a lower rate of pressure increase. Their respective highest pressures were approximately equal to that of lower water content samples (9 wt % and 12 wt %, respectively). The 25-min 6 wt % LMS-1 runs reached an average maximum pressure of 10.0 mbar while the 30-min 6 wt % LMS-1 sample reached an average maximum pressure of 10.7 mbar with a clear peak at 25 min.

The temperature of the samples was measured every 5 min using the pyrometers (Fig. 7). In general, the temperatures of all LHS-1 samples reached higher temperatures than LMS-1 samples. For LHS-1 samples, a trend is seen in that the lower the water content of the samples, the higher the peak temperature at 25 min. Such a trend was not seen for LMS-1 samples. Much lower gaps are seen between the final temperatures of different water content LMS-1 samples.

Fig. 6. Top) Average pressures for all LHS-1 samples. Bottom) Average pressures for all LMS-1 samples. Pressures were recorded in an open system. Therefore, pressure measurements can be used to indicate trends but cannot be used to calculate volumes and quantities of gas present. Errors are smaller than the data points.
Acta Astronautica 209 (2023) 95–103

25-min run. This implies that while more efficient heating is possible the respective 25-min run (Fig. 6). There was no peak for the respective cases where the material excavated is significantly different (mare campaign. However, the results in this study show that even in extreme contents, and grain size distributions possible upon each excavation

The choice of 30 min for the additional heating was based on input energy calculations meaning that if the reflected power for a control sample is known, the heating time required to reach a certain mass of extraction could be estimated. When excavating lunar material, the material is likely to be heterogenous with different compositions, water contents, and grain size distributions possible upon each excavation campaign. However, the results in this study show that even in extreme cases where the material excavated is significantly different (mare composition against highland composition), variable heating performance can be overcome with additional heating. The results of this study have shown that different microwave settings for different materials are key to optimising the heating performance. This means any prospecting mission would still require information on the approximate chemical composition of the site to design an optimum heating system or have a heating system that can alter the settings in situ. These settings would involve (i) the resonant microwave frequency for each material with optimised microwave cavity dimensions and (ii) dedicated tuning for minimising reflective power to maximise the sample’s microwave energy absorption. The results indicate that low-power (e.g., 250 W) microwave heating could be used for prospecting missions, with the technique able to extract large fractions of present water ice regardless of the material composition. While a dynamic MHU payload with adjustable settings could maximise the heating efficiency, it has been demonstrated that a simple low-power MHU with non-adjustable settings should still extract enough water for the needs of a prospecting or pilot plant.

On the other hand, within a specific simulant set, i.e., either LHS-1 or LMS-1 samples, there is a linear increase in the water extracted with water content, as expected. Counterintuitively, the quantity of water extracted is lower at the highest water contents. This inflexion occurs at 12 wt % and 15 wt % for LMS-1 and LHS-1, respectively. Previous work determined the saturation points of NU-LHT-2M simulant as 13–17 wt %, similar to the maximum values used here. In fact, the 15 wt % LMS sample was observed to be over-saturated and, therefore, not used in these experiments [30]. The saturation point of a simulant is defined as the point at which the pore spaces between grains are filled with water, and any additional water will cause the separation of the grains. An observed decrease in water extraction occurs at different water concentrations for both simulants. This is due to their differences in porosity. LHS-1 has a porosity 10% higher than LMS-1 and, therefore, can hold more water in the pore spaces [21]. When saturated samples are frozen, the water expands and pushes the grains apart, causing the grain distance to increase and reducing the surface area of contact between neighbouring grains. At this point, there is also a decrease in the ratio of grain surface area over the total surface area of ice as free islands of ice form. Regions of “free ice” are defined as those regions of ice that are not in direct contact with simulant. This does not happen with non-saturated samples as the expanding water ice moves into the free pore space resulting in minimal grain movement. Fig. 8 shows the

![Fig. 7](image7.png)

**Fig. 7.** The average surface temperatures of all the samples run in this study. Surface temperatures indicate an overall temperature trend but do not accurately portray the core temperature of the samples. Errors are small enough not to be seen on this scale. Note that these temperatures indicate the crucible surface, and the ceramic paper in the crucible acts as an insulator. Thus, the actual temperature of the sample core should be higher than the recorded one. However, the data still show a valuable heating trend, as was further discussed in Ref. [16].

Simulants showing quicker thermal runaway. The impact of the other oxides remains unknown. However, Fig. 5 shows no discernible difference in the water extraction of the LHS-1 and LMS-1 samples (once microwave energy adsorption is taken into account) regardless of the water content of the sample, indicating that the difference in composition, and therefore lunar location, has no significant effect on water extraction using microwave energy. Therefore, as a first-order approximation, the use of microwave heating may not be constrained by local geology. Any differences in extraction between the two simulants are assumed to be due to the differences in average absorbed power resulting in reduced heating performance. The reduced heating performance can be inferred from the pressures and temperatures of the samples in Figs. 6 and 7.

LMS-1 samples for any specific water content have lower maximum temperatures than the respective LHS-1 samples (Fig. 7). This is contradictory as mare simulants should show increased temperature gains over highland simulants due to the higher Fe contents. The difference can instead be explained by (i) sub-optimal microwave settings and (ii) lower porosity of lunar mare simulant samples. During the 30-min run for LMS-1 at 6 wt %, a peak in pressure forms at a higher pressure than the respective 25-min run (Fig. 6). There was no peak for the respective 25-min run. This implies that while more efficient heating is possible through optimum settings, lower average absorbed power could be accounted for by simply heating the sample for a more extended period. The choice of 30 min for the additional heating was based on input energy calculations meaning that if the reflected power for a control sample is known, the heating time required to reach a certain mass of extraction could be estimated. When excavating lunar material, the material is likely to be heterogenous with different compositions, water contents, and grain size distributions possible upon each excavation campaign. However, the results in this study show that even in extreme cases where the material excavated is significantly different (mare composition against highland composition), variable heating performance can be overcome with additional heating. The results of this study have shown that different microwave settings for different materials are key to optimising the heating performance. This means any prospecting mission would still require information on the approximate chemical composition of the site to

![Fig. 8](image8.png)

**Fig. 8.** A diagram highlighting the difference in pore space between non-saturated and saturated samples. When a non-saturated sample is frozen, the water expands into the pore space keeping the grains in place and maintaining the same contact area for heat transfer. When a saturated sample freezes, the water has no space to expand into other than outwards and moves the grains apart, reducing the contact area and resulting in less efficient heat transfer. Saturated samples form islands of free ice where the microwaves have a little heating effect due to the low dielectric loss factor of water ice.
5. Conclusions

A simple solution to overcome extraction issues with high water concentration deposits may be to heat the samples for longer, as can be seen when samples were heated for 35 min, where almost all the water was extracted. This study found that using a simple input energy principle (Input Energy = Absorbed Power × Heating Time) to estimate the additional heating time is sufficient to overcome inefficient heating due to sub-optimal microwave settings. The same could be true for inefficient heating due to high water content. However, if significant additional heating is required, it may be better to use conventional heating as a secondary heat source to melt the free ice, whereupon use a microwave heating method as the main heat source to heat the regolith and extract the water ice in contact with the grains. This may be particularly efficient due to the high thermal conductivity of water ice [32]. Another solution would be the use of susceptors. Susceptors are materials that are particularly susceptible to microwave energy [33]. Susceptors can be placed in or around the lunar material, allowing more efficient heating at lower temperatures and higher water contents. Early work has shown this to be a promising method [33].

5. Conclusions

Icy lunar samples made using highland and mare simulants at different water concentrations (3–15 wt %) have been heated using 250 W, 2.45 GHz microwaves. Samples with an initial temperature of <130 K or lower were placed in a microwave cavity with an initial vacuum of 5 mbar. Up to 67% of the water was extracted in 25-min runs, and 90% was extracted after 35 min. There were negligible differences in water extraction between the two simulants despite the differences in composition. The extraction differences found were due to different porosities in the samples. A reduced average absorbed power for one simulant type can be overcome with additional heating. A reduction in water extraction at higher water contents was found for both simulants caused by freezing water pushing the simulant grains apart, reducing the contact area between grains and increasing the size of regions of free ice. Both mechanisms have resulted in less efficient heating and lower quantities of water extraction. Implications of this involve an upper limit on the extraction of water at future mission sites, after which microwave heating could no longer be effective as an extraction technique compared to other heating techniques. Additional heating time, in combination with conventional heating methods, and using susceptors could increase the water extraction efficiency and allow more water-rich sites to be accessed using microwave heating. Developing a dynamic mass instrument to measure the mass of a sample while it is being heated in a microwave environment should allow further investigation of correlations between porosity and water content and their effect on the efficacy of water extraction using microwave heating. While low-power microwave heating is an effective extraction technique, this study concludes that low-power microwave heating as a singular heating method is best suited for site prospecting or water extraction from low-water content mission sites (<10 wt %).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A 1

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<tr>
<th>Simulant</th>
<th>Water Content (wt. %)</th>
<th>Crucible Mass (g)</th>
<th>Frozen Mass (g)</th>
<th>Post-MHU Mass (g)</th>
<th>Desiccated Mass (g)</th>
<th>Initial Water Mass (g)</th>
<th>Water Extracted (g)</th>
<th>Extraction Ratio (%)</th>
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<td>LHS-1 (25 min)</td>
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(continued on next page)
Table A 1

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<th>Frozen Mass (g)</th>
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<th>Initial Water Mass (g)</th>
<th>Water Extracted (g)</th>
<th>Extraction Ratio (%)</th>
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Table A 2

All extraction data for LMS-1 samples.

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<th>Post-MHU Mass (g)</th>
<th>Desiccated Mass (g)</th>
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References


