IAC-21, A3, IP, 5, x64672

Microwave powered extraction of water ice from the permanently shadowed regions on the lunar surface

Kunal M. Kulkarni[a]*, Richal B. Abhang[b]

[a] *Student, Department of Aeronautics and Astronautics, Technical University of Berlin, Straße des. 17. Juni 135, 10623 Berlin, Germany,* k.kulkarni@campus.tu-berlin.de
[b] *Student, Department of Technology, Savitribai Phule Pune University, Ganeshkhind, 411007 Pune, Maharashtra, India,* richalabhang@gmail.com
* Corresponding Author

Abstract

The future of space exploration is highly dependent on In-Situ Resource Utilisation (ISRU) technologies which will harness the resources that are readily available on various planetary bodies. It will be crucial for keeping the prospective space settlements sustainable and independent from Earth. Moon is a place of high focus for developing a human settlement as it is currently most accessible from Earth and has useful resources like water which can be used for multiple applications like production of oxygen for the crew, production of hydrogen for fuel cell-powered machines, etc. This paper will discuss a special technique developed to extract water trapped inside the lunar regolith located in the moon's Permanently Shadowed Regions (PSRs) as discovered by the previous moon missions. In this method, microwaves will penetrate through the top regolith layers and heat the water ice trapped inside it. This will lead to the sublimation of water molecules along with any other volatiles present there which can be collected for further processing. Regolith acts as a natural insulator and will not readily transfer heat via conduction. Microwaves on the other hand have higher chance of penetrating through the regolith layer with comparatively low energy consumption as it does not depend on the thermal conductivity of regolith. There is also no requirement for excavation of the regolith and hence the entire process is practically dustless which is very useful for keeping the onboard machine components safe from the fine and sharp lunar dust particles. This technology can be easily adapted for any size or capacity according to the mission requirements. This paper will compare different microwave frequencies and their results according to the analytical calculations conducted. The validation of the aforementioned claims will be concluded with the help of currently available lunar surface data. Furthermore, this paper will also highlight the scope of this technology.

Keywords: ISRU, Microwave, Dielectric heating, Lunar regolith, Permanently Shadowed Regions, Water ice

Acronyms/Abbreviations

PSRs – Permanently Shadowed Regions

1. Introduction

In the recent years, it was observed that there exist water ice deposits trapped below the surface of lunar regolith located in the PSRs. It was hypothesized that this presence of water was due to the extreme cold temperatures in the shadowed regions that froze the water and hence the deposits stayed intact in these regions. Water being a very useful resource, the next step was to be able to extract this water. The main concern was being able to separate the water ice particles from regolith. The technique described here introduces dielectric heating using microwaves to heat the water ice particles below the regolith cover and volatize them into vapour form. These vapours can then be collected and processed further for the various applications. Using microwaves will solve the problem of encountering lunar dust as there will not be a need for excavation. Also, considering the fact that the regolith acts as a thermal insulator for conductive heating, microwaves will be able to penetrate it in a better and efficient manner.

2. Model Assumptions

The dielectric heating model assumes a homogenous regolith layer to reduce the initial complexity of the analytical calculations as well as due to lack of in-situ data of the regolith present in the PSRs. The regolith porosity is considered to be 40% (Heiken, Vaniman, & French, 1991) [1] and the water ice content is assumed to be 5%. Density of the regolith is assumed homogenous at 2.65 g/cc (Brisset, Miletich, & Metzger, 2020) [2] and the bulk density is calculated accordingly, considering porosity as well as water ice content. The heat capacity of regolith (Cp) is assumed to be 920 J/Kg-K. It is very close to that of sandstone which according to the tests conducted on Apollo samples (Lim & Anand, 2019) [3] is similar enough to the lunar regolith for analytical validation. The volume of regolith under consideration is 1 m^3 (2 x 1 x 0.5 m). The total required rise in temperature is considered to be 30 degrees by calculating the required minimum temperature to thermally volatize the water ice (Engineering Toolbox, 2010) [4]. The average temperature inside the PSRs is taken to be 50 K which will be the initial temperature before thermal extraction starts (Dr. Williams, n.d.) [5].

3. Microwave system specification

The dielectric heating mechanism involves the use of microwaves. For comparative analysis, the calculations are done for two frequencies – 915 MHz and 2.45 GHz- as these are the most widely used in industry today which increases their reliability as well as availability. The electric field inside the microwave cavity is assumed to be 200 V/cm which is the average for any household microwave (Microwave Properties North, n.d.) [6]. A standing wave is assumed to be developed inside the microwave cavity to aid the analytical calculations.

4. Dielectric properties of lunar regolith

The regolith dielectric properties are taken from the NASA JPL published values for the Apollo samples (Barmatz, Steinfeld, Winterhalter, Rickman, & Weinstein) [7]. In this paper the average of the mare and highland regolith dielectric properties is considered for better approximation. The dielectric permittivity (ε') is approximated to 2.735 and the dielectric loss factor (ε'') is averaged to 0.02435.

5. Analytical model for heating lunar regolith in microwave field

The analytical modelling of heating a dielectric material in an electromagnetic field involves the calculation of the amount of energy deposited by the microwave in the material. This energy can be initially calculated in the terms of electric field intensity produced in the substance in the presence of a given electromagnetic field. This electric field will result into a thermal energy deposition in the dielectric which will eventually result into its rise in temperature. Then, we compare this value with the required change in temperature and then adjust the remaining input parameters accordingly.

5.1 Electric field intensity

As a result of the microwave, an electric field will be induced in the regolith volume.

According to the assumptions, there will exist two components of the electric field – parallel and perpendicular. The electric field calculations were referenced from (Microwave Properties North, n.d.) [6]

5.1.1 Parallel component of the electric field

$$E_{par} = \frac{\left(Eext/\sqrt{2}\right)}{\left[1+Fshpar\left[\left(\varepsilon'^{2}+\varepsilon''^{2}\right)^{0.5}-1\right]\right]}, \qquad (1)$$

where E_{par} = electric field intensity in the direction parallel to the regolith surface in V/cm, E_{ext} = electric field inside the microwave cavity in V/cm, F_{shpar} = shape factor considering parallel arrangement which is taken as 0.1, ε' = dielectric permittivity, ε'' = dielectric loss factor.

5.1.2 Perpendicular component of the electric field

$$E_{perp} = \frac{\left(Eext/\sqrt{2}\right)}{\left[1+Fshperp\left[\left(\varepsilon'^{2}+\varepsilon''^{2}\right)^{0.5}-1\right]\right]} \qquad (2)$$

where E_{perp} = electric field intensity in the direction perpendicular to the regolith surface in V/cm, F_{shperp} = shape factor considering perpendicular arrangement which is taken as 1.5 for the considered rectangular cross section, and the rest of the parameters are same as that for the parallel component.

The electric field deposited in the regolith volume gives the amount of energy effectively absorbed by the regolith particles. This results into a rise in the temperature of the regolith and is more efficient than conductive heating as regolith has very low thermal conductivity of around 2 x 10^{-4} W/cm-K (Heiken, Vaniman, & French, 1991) [8]. For a relative comparison, a good thermal conductor like aluminium has a thermal conductivity of around 2.4 W/cm-K (Carvill, 1993) [9].

5.2 Power deposited per unit volume

The power deposited by the microwave field into the regolith volume is calculated by

$$P = \left(\frac{1}{2}\right) \times \omega \times \varepsilon 0 \times \varepsilon'' \times \left(Epar^{2} + Eperp^{2}\right), \quad (3)$$

where P = power deposited per unit volume in Watt/cc, ω = angular frequency of the microwave generated in rad/s, $\varepsilon 0$ = permittivity of free space, ε'' = dielectric loss factor, E_{par} and E_{perp} are the parallel and perpendicular electric field components respectively. The power deposited gives the amount of thermal power in Watt which can be used to calculate the heat energy deposited by the microwave in the regolith volume.

5.3 Heat energy Deposited

In this part of calculations, we now move towards the calculation of thermal energy generated as a result of the microwave. The amount of heat energy deposited is calculated by:

$$Q = P \times t \times V \tag{4}$$

derived from the thermodynamic formula for power, where Q = Heat energy deposited in the regolith volume in Joule, t = time of heating in seconds, V = regolith volume under consideration in cubic centimetre.

Q is the most important variable in this technique as it represents the amount of heat energy used for heating the regolith. This can be used for calculating the change in temperature of the regolith volume under consideration.

5.4 Change in temperature of the regolith volume

Using the heat energy calculated in the previous step, we can use the equation

$$Q = m \times Cp \times \Delta T, \tag{5}$$

to calculate the rise in temperature of the regolith volume, where, m = mass of regolith in gram, Cp = Heat capacity of regolith in Joule/kg-K, ΔT = rise of temperature.

This value concludes the initial analytical calculations as this represents the final value of the regolith volume temperature after heating. It is then used to find out the input variables in order to get the required amount of temperature change.

6. Results

According to the aforementioned equations, the following results were recorded for the regolith volume under consideration:

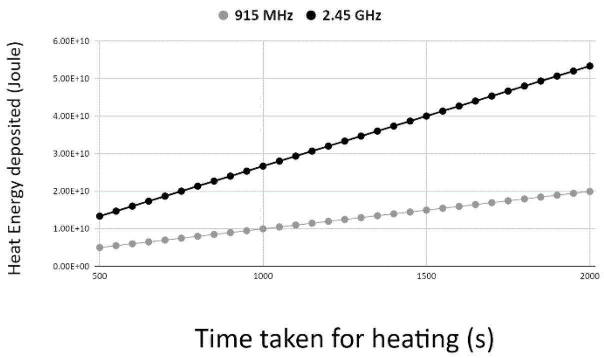

Fig. 1. Heat energy deposited v/s time taken for heating

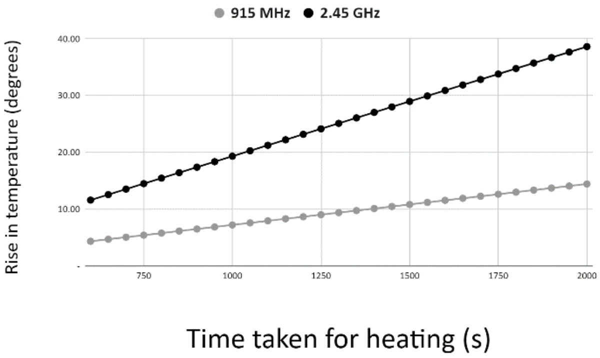

Fig. 2. Rise in temperature v/s time taken for heating

f (MHz)	P (Watt/cc)	t (s)	Q (Joule)	ΔT
915	9.96	5000	4.89E+10	36.08
2450	26.66	2000	5.33E+10	38.64

Table 1.1. Results of analytical calculations

According to the results shown in figures above, the 2.45 GHz microwave is evidently more effective to deposit more than twice the amount of heat energy as that deposited by the 915 MHz microwave within the same time interval. As a result of which, the regolith volume is twice as heated by the 2.45 GHz compared to that by the 915 MHz microwave. This brings us to the selection criteria of the microwave frequency. The current analytical calculations along with the available lunar surface data suggest that the 2.45 GHz will be a better alternative. This is assuming that the depth of water ice present is within the range of penetration of the 2.45 GHz microwave, else there will be a need to reassess the data for deeper water ice presence as the 915 MHz will have higher depth penetration owing to its longer wavelength. However, this can only be decided once any in-situ data for the PSRs is available. Until then, our research will focus on comparative study of both the microwave frequencies.

7. Scope of Technology

The technology described in this paper is not restricted for implementation on the lunar surface. This technique of extracting water from the lunar surface can be employed for extracting volatiles on any other space objects with minimal modifications according to the respective working environment. It can very well be used to extract valuable volatiles like water or other gases from the depths of other planets, satellites, asteroids, etc.

8. Conclusions

The results conclude that the microwave extraction of water ice can be done in very less time and can yield usable amounts of water ice which can prove useful for future moon as well as other space settlement missions. The current research goal is focused towards analytical feasibility study of the technique after consideration of various losses such as the heating losses, loss of volatiles through the porous layer of regolith as well as internal electrical losses. The next phase of research will involve development of simulation models using multi-physics tools to conduct tests for various values of the parameters to find out the most energy- and cost-efficient solution. The team is also working on developing a test setup for demonstrating the technique in laboratory environments as a proof of concept of the working principle. The focus of our research is to make this technology scalable and feasible for all future human space missions and make in-situ resource utilization more reliable for future human space settlements.

References

[1] Heiken, G. H., Vaniman, D. T., & French, B. M. (1991). *Lunar Sourcebook.* New York: Cambridge University Press, pg 515.

[2] Brisset, J., Miletich, T., & Metzger, P. (2020). Thermal extraction of water ice from the lunar surface - A 3D. *Planetary and Space Science, 193*(2020), 3-3.

[3] Lim, S., & Anand, M. (2019). Numerical modelling of the microwave heating behaviour of lunar regolith. *Planetary and Space Science*.

[4] Engineering Toolbox. (2010). *Water - Boiling Points at Vacuum Pressure*. Retrieved from Engineering Toolbox: https://www.engineeringtoolbox.com/water-evacuation-pressure-temperature-d_1686.html

[5] Dr. Williams, D. R. (n.d.). *Moon Fact Sheet*. (NASA) Retrieved 05 2021, from nssdc.gsfc.nasa.gov: https://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html

[6] Microwave Properties North. (n.d.). *Microwave heating problem*. Retrieved 05 2021, from Microwave Properties North: http://www.microwavepropertiesnorth.ca/heating/

[7] Barmatz, M., Steinfeld, D., Winterhalter, D., Rickman, D., & Weinstein, M. (n.d.). *Microwave Heating Studies and Instrumentation for Processing Lunar Regolith and Simulants.* California: National Aeronautics and Space Administration.

[8] Heiken, G. H., Vaniman, D. T., & French, B. M. (1991). *Lunar Sourcebook.* New York: Cambridge University Press, pg 62.

[9] Carvill, J. (1993). 3.14.5 Thermal conductivity coefficient. In J. Carvill, *Mechanical Engineer's Data handbook* (pp. 102-145). Elsevier.