Joule-heated Molten Regolith Electrolysis Reactor Concepts for Oxygen and Metals Production on the Moon and Mars

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• The maturation of Molten Regolith Electrolysis (MRE) as a viable technology for oxygen and metals production on explored planets relies on the realization of the self-heating mode for the reactor.

• Joule heat generated during regolith electrolysis creates thermal energy that should be able to maintain the molten phase (similar to electrolytic Hall-Héroult process for aluminum production).

• **Self-heating via Joule heating offers many advantages:**
  - The regolith itself is the crucible material → protects the vessel walls
  - Simplifies the engineering of the reactor
  - Reduces power consumption (no external heating)
  - Extends the longevity of the reactor

• Predictive modeling is a tool chosen to perform dimensional analysis of a self-heating reactor:
  - Multiphysics modeling (COMSOL) was selected for Joule heat generation and heat transfer
  - Objective is to identify critical dimensions for first reactor prototype
Self-heating Hall-Hérout reactor (Aluminum)

$2O^{2-} + C \rightarrow CO_2 + 4e$

$Al^{3+} + 3e \rightarrow Al_{(V)}$

Carbon

Molten fluoride + $Al_2O_3$

Anode

Bath

Aluminum

Lining

Collector Bar

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\[(\text{FeO}_x) \rightarrow \text{Fe}_{(\text{Fe})} + \frac{x}{2} \text{O}_2\]

Diagram showing the process of molten regolith electrolysis with labels for various components such as anode, cathode, electrolyte, and metal pool.
Electrowinning

Anode

Cathode

Cathodic product

O₂
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REACTOR MODEL

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Heat Transfer Modeling

General Energy Equation for solids
\[ \rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q \]

Heat Sources
\[ Q = Q_j + Q_r \]

**Joule heating**
\[ Q_j = \frac{1}{\delta} J^2 \]

**Thermal radiation in participating media**

Radiative Intensity for gray & isotropic medium
\[ \nabla I(r,s) = k_s I_b(T) - (k_a + \sigma_s) I(r,s) + \frac{\sigma_s}{4\pi} \int_0^{2\pi} I(r,s') p(s',s) d\Omega' \]
- change in radiative intensity
- emission
- absorption
- scattering

This equation needs to be integrated over the spatial as well as the angular domain. Spatial discretization is done by dividing spatial domain into discrete control volumes or cells. The angular discretization is done using control angles.

The radiation direction vector \( s \) is defined in terms of two angles \( \alpha \) and \( \beta \)
\[ G = \sum I(r,s) \]
\[ Q_r = k_a (G - 4\sigma T^4) \]

**Boundary Conditions**
- Radiative heat transfer between outer surfaces and ambient.
- Radiative heat transfer between outer surfaces
- Free convective heat transfer with ambient
- Constant voltage at the top of anode lead
- Electrical ground at the top of cathode collector
- Thermal insulation at the outer bottom of the cell
- All surfaces electrically insulated

\( \rho, C_p, k, \sigma_s, \sigma_a, T, J = \) density, heat capacity, thermal conductivity, electrical conductivity, temperature, current density

\( r, s, \Omega, \Phi, \beta = \) direction vector, position vector, variable for control angle direction, scattering phase function, scattering coefficient

\( I(r,s), I_b, G = \) radiative intensity at \( r \) position and \( s \) direction, black body intensity, incident radiation within the participating media
Thermophysical Properties of regolith

Thermal Conductivity

Electrical conductivity

Heat Capacity

Density

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Optical Absorption

Absorption coefficient

Lunar glassy spherules obtained from lunar dust brought to earth by Apollo 14 mission

Commercial glass (clear and gray) and bronze
Initial temperature: 25 °C
Preheating temperature: 1,700 °C

Potential (Volts)

Heat dissipation (W/m$^3$)

Temperature (°C)
### Relevance of Thermal Radiation Within Participating Media

<table>
<thead>
<tr>
<th>Neglected</th>
<th>Included (k=100 m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>Molten Phase</td>
</tr>
<tr>
<td>850</td>
<td>3,250</td>
</tr>
<tr>
<td>50</td>
<td>80</td>
</tr>
</tbody>
</table>

Applied Voltage: 34 V at the anode lead that yields 15 V at the molten phase.
RADIATION HEAT SOURCE WITHIN PARTICIPATING MEDIA

Total yield (W/m^3)

Absorption yields (W/m^3)

Emission yields (W/m^3)

Applied Voltage: 34 V at the anode lead that yields 15 V at the molten phase.

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OPTICAL ABSORPTION EFFECT ON MOLTEN PHASE FORMATION

$k = 0 \text{ m}^{-1}$

$k = 100 \text{ m}^{-1}$

$k = 300 \text{ m}^{-1}$

Applied Voltage: 34 V at the anode lead that yields 15 V at the molten phase.
Temperature profile of irradiated JSC-1A melts predicted by the model using Orbitec experimental conditions.

Solidified half-sphere produced by focused solar beam (Orbitec/PSI Corp.)
EFFECT OF ANODE GEOMETRY

Regolith Temperature profile under a flat anode at 34 V.
Max. melt temperature: 1,437 °C

Regolith Temperature profile under a waffle anode at 34 V.
Max. melt temperature: 1,437 °C
CONCLUSIONS

• The modeling of all modes of heat transfer within a self-heating Molten Regolith Electrolysis reactor can be useful tool to investigate the parameters driving its design.

• The heat transfer modeling performed so far confirms the feasibility of self-heating MRE reactors for electrolytic reduction of lunar oxides from their own melt.

• It also confirms that another technique is required to achieve the formation of the melt from the regolith at ambient conditions before activating the electrolysis and the self-heat mode.

• The combination of high surface area geometries for anodes, distributed electrical connections and adjustments of inter-electrode gaps were found to have strong effects on the overall power efficiency performance and thermal performance of Joule-heated MRE reactors for electrolytic reduction of lunar oxides from their own melt. Preliminary findings suggest that the minimum critical size of such reactor may be on the order of a cubic foot in volume with a power requirement of less than 5 kW.

• The engineering of prototype reactors designed to process regolith in space at melting temperatures will require the knowledge of these and other fundamental properties of the various mineral resources.
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QUESTIONS?