Design and Test of a Concentrated Solar Powered Fluidized Bed Reactor for Ilmenite Reduction

... on the Moon

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Motivation

• When travelling to space, you have to bring *everything* with you.
• Up-mass is reduced significantly if local resources can be used (*In-Situ Resource Utilization*, ISRU).
• When travelling beyond LEO, more than 50% of the mass is *oxygen*.
• Most abundant element on the Moon is *oxygen*.

=> Oxygen extraction from lunar soil is very attractive.
=> Goal is to build a terrestrial demonstrator.
Lunar Oxygen Production Processes

FeTiO$_3$ + H$_2$ $\rightarrow$ Fe + TiO$_2$ + H$_2$O \hfill (1)

H$_2$O $\rightarrow$ H$_2$ + $\frac{1}{2}$ O$_2$ \hfill (2)


### TABLE III
Qualitative Comparison of Lunar Oxygen Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Technology$^a$</th>
<th>No. of Steps$^b$</th>
<th>Process Conditions$^c$</th>
<th>Feed-Stock$^d$</th>
<th>Total</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ilmenite red. with H$_2$</td>
<td>8</td>
<td>9</td>
<td>7</td>
<td>3</td>
<td>27</td>
<td>4</td>
</tr>
<tr>
<td>Glass red. with H$_2$</td>
<td>7</td>
<td>9</td>
<td>7</td>
<td>6</td>
<td>29</td>
<td>2</td>
</tr>
<tr>
<td>Molten sil. electrol.</td>
<td>6</td>
<td>8</td>
<td>5</td>
<td>10</td>
<td>29</td>
<td>3</td>
</tr>
<tr>
<td>Vapor phase reduction</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>10</td>
<td>30</td>
<td>1</td>
</tr>
</tbody>
</table>

$^a$ Technology: 1 = major technologic development required; 10 = no major unknowns.

$^b$ No. of steps: 1 = many (>5); 10 = one step.

$^c$ Process conditions (temperature, energy, plant mass, corrosion): 1 = severe; 10 = low.

$^d$ Feedstock requirements: 1 = huge quantities; 2 = mare, beneficiated (ilm); 5 = mare, unbeneificted; 10 = any feedstock, unbeneificated.
Fluidized Bed Reactor

- Reactor Vessel
- Aperture Cone
- Quartz Window
Fluidized Bed Reactor
Particles Feed
Particles Removal
Gas Treatment ("Downstream")

Cooler 1
Cooler 2
Water Separator
Water Extraction Pump
Particles Separator (T>100°C!)
Goals, Particles, Test Phases...

1. Identify the gas flow demand of the main (+auxiliary) fluidized bed(s) in the reactor as a function of the temperature.
2. Demonstrate continuous operation, especially particles feed and removal.
3. Operate the reactor at 800°C – 1000°C solely heated with concentrated solar power.
4. Demonstrate water production from the reaction of the ilmenite with hydrogen.

- Particles: Pure Ilmenite, 150µm (sorry, no real Moon rocks yet 😞)
- Gas: Argon, with up to 10% H₂

Phase 1: Air, 400°C (5 tests)
Phase 2: Argon, 800°C (6 tests)
Phase 3: Argon + Hydrogen, 950°C (11+4 tests)
Solar Tests
Oresol – Solar Tests
Oresol – Solar Tests
Fluidization Gas Demand

\[ \dot{V}_{mf} \sim \frac{1}{T^{1.7}} \]

\[ \dot{V} \sim \frac{1}{T} \]
Power Balance
Power Balance

\[ P_{IR} = \varepsilon A \sigma T^4 \]
• Water came out 😊
• Water separator worked well
• Low quantity (due to low H₂ feed)
• H₂-conv. > 50%
• Water very acidic (pH=3) and contaminated (NH₄⁺, Cl⁻, …)
• More investigation required
Summary and Outlook

- Solar Thermal Fluidized Bed Reactor for Continuous Operation including Auxiliary Components (especially Off-Gas Treatment) Designed and Built.
- Initial Goals achieved:
  - Automatic Main Gas Flow Control Parameters Identified
  - Continuous Operation incl. Particles Feed and Removal Demonstrated
  - >950°C in the Bed
  - H₂O Production Demonstrated
- Work ahead:
  - Increase Hydrogen Quantity / Percentage / Conversion
  - Use more "Moon-like" Particles (Mix JSC-1A + 10-20% Ilmenite)
  - Testing with 100% Hydrogen
  - Demonstrate Water Production of 0.7kg/h
- Develop Lightweight Solar Concentrator
- Adaption to Real Lunar Conditions (Vacuum, Low Gravity, Regolith...)
- Other Use? (Lunar Poles, Mars. On Earth?)
THANK YOU!

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Solar Concentrator ("Mussel")