IEA-HIA Task 32 “Hydrogen-based Energy Storage”
Hydrogen storage in porous materials

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Outline

- IEA Hydrogen TCP Task 32 “Hydrogen-based energy storage”
  - Introduction and working groups
- Motivation
- Storage by physisorption of hydrogen
- Gravimetric storage capacity
- Volumetric storage capacity
- Conclusion
- Outlook Task 40
Task 32 “Hydrogen-based energy storage”

Goals and objectives

I. Develop reversible or regenerative hydrogen storage materials fulfilling the technical targets for mobile and stationary applications

II. Develop the fundamental and engineering understanding of hydrogen storage materials and systems that have the capacity to fulfil Target I

III. Develop materials and systems for hydrogen-based energy storage including hydrogen storage for use in stationary, mobile and portable applications, electrochemical storage, and solar thermal heat storage
Task 32

Synthesis and characterization of novel materials for hydrogen-based energy storage

**TRL 1-3**

- Hydrogen storage for stationary applications
- Hydrogen storage for mobile applications
- Heat storage for concentrated solar thermal
- Electrodes for Li-ion batteries

**TRL 3-4**

- Hydrogen compressors
- Metal-hydride batteries

**TRL 7-9**

- TRL 7-9
- TRL 7-9
Dissemination in special issues

Hydrogen-based Energy Storage
Applied Physics A - Topical Collection

Foreword plus 21 papers

Special Issue Task 32
Part of final report
7 papers submitted
Task 32 working groups

- Porous materials (coordination polymer framework compounds, MOFs, ZIFs, COFs, and carbons)
- Magnesium-based hydrogen and energy storage materials
- Complex and liquid hydrides (borohydrides, alanates, amides/imides-systems, reactive hydride composites and rechargeable liquid hydrogen carriers)
- Electrochemical storage of energy (MH-batteries, ion-conduction)
- Heat storage – concentrated solar thermal using metal hydrides
- Hydrogen storage systems for mobile and stationary applications
Motivation

IPCC PRESS RELEASE

8 October 2018

Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C approved by governments

INCHEON, Republic of Korea, 8 Oct - Limiting global warming to 1.5°C would require rapid, far-reaching and unprecedented changes in all aspects of society, the IPCC said in a new assessment. With clear benefits to people and natural ecosystems, limiting global warming to 1.5°C compared to 2°C could go hand in hand with ensuring a more sustainable and equitable society, the Intergovernmental Panel on Climate Change (IPCC) said on Monday.

Motivation

NEWS  ·  08 OCTOBER 2018

IPCC says limiting global warming to 1.5°C will require drastic action

Humanity has a limited window in which it can hope to avoid the worst effects of climate change, according to climate report.

Jeff Tollefson

Limiting global warming to 1.5°C may still be possible

Climate report puts geoengineering in the spotlight

Bring climate change back from the future

How scientists reacted to the US leaving the Paris climate agreement

Glaciers and sea ice won’t be safe in a world that warms to 2°C above pre-industrial levels. Credit: NASA/Mark Eshleman
Fuel Cell vs Battery Electric Vehicles

Comparative Analysis of Infrastructures:
Hydrogen Fueling and Electric Charging of Vehicles

Martin Robinius, Jochen Linßen, Thomas Grube, Markus Reuß, Peter Stenzel, Konstantinos Syranidis, Patrick Kuckertz and Detlef Stolten

Energy & Umwelt / Energy & Environment, Band / Volume 408, January 2018

http://juser.fz-juelich.de/record/842477/files/Energie_Umwelt_408_NEU.pdf
The technology is here and working

In the summer of 2016 BeeZero was launched in Munich as the world’s largest and friendliest carsharing with hydrogen to show that fuel cell vehicles are absolutely suitable for everyday use and to give you the opportunity to experience emission-free hydrogen mobility first hand. Together with you we have achieved this:

- You’ve covered nearly 400,000 zero-emission kilometers
- Our vehicles have been traveling with you for more than 60,000 hours
- Together we have saved almost 40,000 kg of CO₂
Current high pressure storage

- Toyota 2018 Mirai
- 70 MPa
- 5 kg H₂
- 122.4 L
- 41 gH₂/L
- 87.5 kg
- 5.7 wt%

System: 5 wt% and 40 g/L

Hydrogen storage in solids

Chemisorption
- dissociation
- strong bond
- 30 – 100 kJ/mol

Physisorption
- molecules
- van der Waals
- 1 – 10 kJ/mol

Advantages:
- reversible
- fast kinetics
- but, low temp.

Surface area!
Metal-organic frameworks (MOFs)
Gravimetric absolute H$_2$ uptake at 77 K
Gravimetric capacity and Chahine’s rule

Activated carbons
R. Chahine, T.K. Bose, Proc. 11th WHEC Stuttgart, Dechema, Germany 1996

Hydrogen surface density at 77 K

\[ 1.9 \cdot 10^{-2} \text{ mg/m}^2 \]
Gravimetric to volumetric capacity

Density: **Single crystal density (XRD)**

**Packing density**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUT-6</td>
<td>0.31</td>
</tr>
<tr>
<td>DUT-8 (Cu)</td>
<td>0.28</td>
</tr>
<tr>
<td>MOF-177</td>
<td>0.26</td>
</tr>
<tr>
<td>AX21_33</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Dead space

Packed volume of material

**Pelletizing and shaping**

Hydrogen cryo-adsorption by hexagonal prism monoliths of MIL-101
Packing density → total volumetric capacity

Total volumetric uptake at 77 K

Total gravimetric uptake at 77 K

PAF-1 porous aromatic framework
Vol. H$_2$ uptake at 77 K / vol. surface area

Hydrogen surface density at 77 K

$1.9 \cdot 10^{-2}$ mg/m$^2$


Specific volume (1/density) vs specific surface area

R. Zacharia, D. Cossement, L. Lafi, R. Chahine

\[
\frac{1}{\rho} = \alpha \cdot \sigma + V_0
\]

Volumetric vs gravimetric H$_2$ uptake at 77 K

\[ n_v = \frac{\alpha}{\kappa} \cdot n_g + V_0 \]

Adsorbent Heat Exchanger Types

**HexCell**
Flow Through Chilled H$_2$ Cooling

**MATI**
Isolated LN2 Flow Cooling

700 bar compressed hydrogen

Gain Volumetric Density
in going from loose powder to compacted pucks
at expense of Cost
Conclusion

Hydrogen storage by physisorption on MOFs

B Current status
- Fast kinetics and reversibility
- Large specific surface area limit 4500 - 5000 m$^2$/g
- High gravimetric storage capacity at 77 K and < 5 MPa excess ~ 8 wt%, total 12 – 15 wt% 
- Volumetric absolute capacity
  - powder 20 g/L → monoliths 30 g/L (total 40 g/L)
  - single crystal 40 g/L → interpenetrated 50 g/L

B Future challenges
- Increase volumetric capacity → interpenetrated structures
- Increase usable capacity → flexible frameworks
Outlook

- **Task 40 “Energy storage and conversion based on hydrogen”**
- **Duration:** January 1, 2019 til December 31, 2021
- **Planed working groups**
  - Porous materials (coordination polymer framework compounds, MOFs, ZIFs, COFs, and carbon-based compounds)
  - Magnesium- and intermetallic alloys-based hydrides for energy storage
  - Complex hydrides (borohydrides, alanates, amides/imides-systems, magnesium-based compounds, reactive hydride composites
  - Ammonia and reversible liquid hydrogen carriers
  - Catalysis
  - Electrochemical storage of energy (MH-batteries, ion-conduction)
  - Hydride-based thermal energy storage
  - Research and development for hydrogen storage and compression
2019 Hydrogen-Metal Systems GRC

Hydrogen-Metal Systems
Gordon Research Conference

Understanding the Interaction of Hydrogen with Materials from the Atomic Level to Systems

June 30 - July 5, 2019

Chairs
Ned T. Stetson and Michael Hirscher

Vice Chairs
Tom Autrey and Ping Chen

- Hydrogen in Space
- Advanced Characterization Methods
- Selected Poster Presentations
- Catalysts and Materials for Hydrogen Carriers
- Current Understanding of Hydrogen Embrittlement
- Advancements in Porous Materials for Hydrogen Adsorption
- 2D Materials and Thin Films
- Boro- and Complex Hydrides
- Developing Applications for Hydride Materials

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Thank you for your attention!

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