A Joint Theory and Experimental Project in the High-Throughput Synthesis and Testing of Porous COF and ZIF Materials for On-Board Vehicular Hydrogen Storage

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Overview

Timeline
Project start date: 9/1/2008
Project end date: 1/31/2013
Percent complete: 5%

Barriers
Barriers addressed
- Improved gravimetric and volumetric density of hydrogen uptake
- Hydrogen capacity and fast kinetics at 77 K
- Improved hydrogen binding energy
- Synthetic scale up of COFs/ZIFs to cubic meters

Budget
- Total project funding
  - DOE share: $1.38 M
- Funding received in FY08: $75 K
- Funding for FY09: $400 K

Collaborating Partner
- BASF
Objectives

*Room temperature \( \text{H}_2 \) storage in COFs and ZIFs to meet DOE 2010 Targets*

- Synergistic work between Yaghi (UCLA) and Goddard (Caltech)
- High-throughput computational screening to identify new materials for favorable \( \text{H}_2 \) uptake
- High-throughput preparation/characterization of doped materials predicted for high uptake
- High-throughput screening to testing a diverse set of compositions and structures
- Develop chemistry and perform computational testing of Li/Na/K doping effects on \( \text{H}_2 \) uptake
- Predict and determine heat evolved upon reversible uptake and release
Milestones

Year 1
1. Develop new force fields for modeling adsorption properties of ZIFs and COFs. Test models using reported adsorption data for a range of known ZIFs and COFs.

2. Experimentally explore metal impregnation conditions in existing ZIFs and COFs, and characterize metal density in the frameworks. Compare with predictions from theory.

3. Investigate pressure and temperature dependence of H₂ uptake in impregnated existing ZIFs and COFs over the parameter range specified in DOE YR2010 guidelines (6 wt % and 45 g L⁻¹ up to 100 bar, -30/50 °C). Compare with predictions from theory.

4. Discover new ZIF and COF materials utilizing high-throughput methods and explore hydrogen uptake properties of ZIFs and COFs in the same parameter range.
Description of new materials

Covalent Organic and Zeolitic Imidazolate Frameworks (COFs and ZIFs)

- COFs are lightweight materials
- ZIFs are highly stable materials
- COFs and ZIFs are suitable towards light metal impregnation

COF-108
ZIF-8
Covalent Organic Frameworks (COFs)

- BDBA
- BTBA
- TBPA
- BPDA
- TBPM (X = C)
- TBPS (X = Si)

COF-1
COF-5
COF-6
COF-8
COF-10
COF-102 (X = C)
COF-103 (X = Si)
Low density crystalline 3D COFs

COF-105
\( (d = 0.18 \text{ g cm}^{-3}) \)

COF-108
\( (d = 0.17 \text{ g cm}^{-3}) \)

Science 2007
Gravimetric excess and total H$_2$ uptake of COFs at 77 K
COF-105 will have the highest uptake (excess 10% and total 20%)

Goddard’s calculations

S. S. Han, H. Furukawa, O. M. Yaghi, W. A. Goddard:
Accomplishments: High-pressure $\text{H}_2$ isotherms of COFs at 77 K

Surface excess mass

$\text{H}_2$ uptake in 3D COFs is almost same as that in MOF-177.
Accomplishments: High-pressure H₂ isotherms of COFs at 298 K

Gravimetric excess H₂ uptake

Volumetric total H₂ uptake

Better volumetric H₂ density compared to compressed H₂
Accomplishments: Modeling study of new 3D COFs

<table>
<thead>
<tr>
<th>Material</th>
<th>BET area / m² g⁻¹</th>
<th>Pore volume / cm³ g⁻¹</th>
<th>Density / g cm⁻³</th>
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</thead>
<tbody>
<tr>
<td>COF-192</td>
<td>3157</td>
<td>1.04</td>
<td>0.627</td>
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<td>COF-212</td>
<td>6711</td>
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</tr>
</tbody>
</table>

H₂ uptake in COFs will be simulated using GCMC simulation with *ab-initio* based FFs.
Approach 1: Post-synthesis modification of COFs (e.g. Impregnation of COFs with metals)

N-containing building units

Various connectivity
Theoretical prediction of binding energy

Model system:

\[(\text{BPyDC})M(CO)_4\]$_2^-$

- $M^{n+} = \text{Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, and Zn (}n\text{ = 0, 1 and 2)}$
- Preliminary DFT calculations

\[\text{[(BPy)V}^{2+}\text{]}(H_2)_4\]

$n = 0$: Mn has stronger binding energy to BPyDC than its cohesive energy.

$n = 1$: Mn$^+$, Co$^+$, Ni$^+$, Cu$^+$, and Zn$^+$ have stronger binding energy to the ligand.

$n = 2$: All metals are favorable for formation of (BPyDC)$M^{2+}$ complexes. Metal impregnated materials would be experimentally accessible

Interaction between H$_2$ molecules and the (BPyDC)$M^{2+}$

(BPyDC)$M^{2+}$(H$_2$)$_4$ average H$_2$ binding energies per one H$_2$ molecule:

-24.6 kJ mol$^{-1}$ for Zn$^{2+}$ to -62.2 kJ mol$^{-1}$ for V$^{2+}$

⇒ These are ideal values for H$_2$ storage at room temperature.
Approach 2: Impregnation/intercalation of COFs with metals

$\eta^5$-Cp-Li system seems versatile and stable rather than $\eta^6$-benzene-Li system.

- Build model structures (e.g. known 2D and 3D COF structures)
- Estimate H$_2$ uptake behavior at room temperature
- Discover experimental materials
Zeolitic Imidazolate Frameworks (ZIFs)

Synthesis of ZIFs

**Extensive class of functionalized linkers**

- IM
- mlM
- elM
- nM
- dclM
- blM
- Pur
- cblM
- mblM

**Various metal sources**

- Design of composition (metal centers and organic linkers). Synthesis and structural characterization is well worked out.
- Control of structure, topology, interpenetration and porosity.
- High-throughput technique is available for quick screening.

More than 50 ZIFs have been discovered by high-throughput methods.
Designed porosity and functionality in ZIFs

Accomplishment: H$_2$ uptake in ZIFs

ZIF-68: Zn(NO$_2$-IM)(BzIM)
ZIF-69: Zn(NO$_2$-IM)(ClBzIM)
ZIF-78: Zn(NO$_2$-IM)(NO$_2$-BzIM)
ZIF-79: Zn(NO$_2$-IM)(Me-BzIM)
ZIF-81: Zn(NO$_2$-IM)(Br-BzIM)
ZIF-82: Zn(NO$_2$-IM)(CN-IM)
Accomplishment: High pressure H₂ isotherms of ZIFs

Poor H₂ uptake at room temperature.
Approach 3: Post-synthesis modification of ZIFs
(e.g. potential halogen-lithium exchange)

\[
\text{Zn(NO}_3\text{)}_2 \quad \text{or} \quad \text{Co(NO}_3\text{)}_2
\]
Summary

Relevance: For room temperature hydrogen storage, a systematic survey was started experimentally as well as theoretically.

Approach: Aim at increasing strong binding sites for maximum hydrogen uptake capacity without losing pore volume.

Technical accomplishments and progress:
- High pressure $\text{H}_2$ uptake behavior in COFs
- Synthesis of new ZIFs for metal impregnation
- Began modeling study for optimal materials

Technology transfer/collaborations: Active relationship with collaboration partners and BASF.

Proposed future research:
- Employ light weight metals to create strong binding sites.
- Material design based on theoretical prediction.