No Vapor-compression, Electrochemical-Loopng Heat Pump (NOVEL HP)

Ray W. Herrick Laboratories, Purdue University; University of Illinois Urbana-Champaign (UIUC)
PIs: Davide Ziviani (Lead), James E. Braun, Eckhard A. Groll, Jeffrey S. Moore, Joaquin Rodríguez-Lopez
RAs: Junyoung Kim, Yunyan Sun, Abhiroop Mishra, Elias N. Pergantis, Sazzad Hossain
PI Email: dziviani@purdue.edu

Made by Junyoung Kim
Project Summary

Timeline:
Start date: Jun 1, 2019 (effective Dec 1, 2020)
Planned end date: Nov 30, 2023

Key Milestones
1. Provide quantitative list of key EWF (Mar 21) and ESM requirements (Jun 21)
2. Down-selection of most promising ELHP system configuration(s) based on complete ELHP system models, including TEA modeling. (Nov 2021)

Budget:
Total Project $ to Date:
• DOE: $999,778
• Cost Share: $283,629

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Key Partners:
Carrier Corporation

Project Outcome:
The overarching goal of this project is to accelerate the development of electrochemical looping heat pump (ELHP) technology, which has the potential to outperform conventional vapor compression systems.

Two major components are investigated:
• New electrochemically active working fluids
• High performance cells

The final project outcome shall be a TRL-3/4 demonstration of a down-selected ELHP system architecture
Team

Members:

- 5 Professors
  - Mechanical Eng. (3)
  - Chemistry (2)

- 4 PhD students
  - Purdue (2)
  - UIUC (2)

- 1 Post Doc.
  - UIUC (1)

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Ph.D. Student in Mechanical Engineering, Purdue Univ.

Elias N. Pergantis
Ph.D. Student in Mechanical Engineering, Purdue Univ.

James E. Braun, Ph.D.
Herrick Professor of Engineering, and Director of the Center for High Performance Buildings, Purdue Univ.

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William E. and Florence E. Perry Head of Mechanical Engineering, and Reilly Professor of Mechanical Engineering, Purdue Univ.

Davide Ziviani, Ph.D.
Assistant Professor of Mechanical Engineering, and Associate Director of the Center for High Performance Buildings, Purdue Univ.

Yunyan Sun
Ph.D. Student, Univ. of Illinois at Urbana Champaign

Abhiroop Mishra
Ph.D. Student, Univ. of Illinois at Urbana Champaign

Sazzad Hossain, Ph.D.
Post Doc., Univ. of Illinois at Urbana Champaign

Jeffrey S. Moore, Ph.D.
Stanley O. Ikenberry Endowed Chair, Professor of Chemistry and Howard Hughes Medical Institute Professor, and Director of Beckman Institute for Advanced Science and technology, Univ. of Illinois at Urbana Champaign

Joaquin Rodriguez-López, Ph.D.
Associate Professor of Chemistry, and a Faculty of Beckman Institute for Advanced Science and Technology, Univ. of Illinois at Urbana Champaign
Challenge

- The buildings' sector in the US accounts for approximately 40% of the primary energy and up to 75% of the electricity produced.

- Conventional HVAC&R Technologies employ high GWP refrigerants that contribute to global warming.

- DOE long term goals:
  - 85% reduction in HFCs by 2035 and transition to low-GWP/natural refrigerants.
  - Alternative HVAC&R technologies.

Source: US DOE EERE-BTO
Challenge (cont’d)

- **Alternative HVAC&R Technologies:**
  - Different development status
  - Reviewed 18+ non-conventional HVAC&R technologies
- **Chemical Looping Heat Pumps:**
  - 20 – 30 % Energy Saving Reported in ELHP (Cooling Mode)
  - High Scalability by Combining with Existing Fuel Cell and Vapor Compression Technologies
  - Ongoing developments in the fuel cell industry and electrochemistry (including selective membranes)

Source: Modified from Goetzler et al., US DOE BTO EERE Report (2014)
## Challenges (cont'd)

- Utilizing Purdue’s expertise in advanced HVAC&R, UIUC’s expertise in electrochemistry, and Carrier’s industrial experience to overcome challenges

<table>
<thead>
<tr>
<th>#</th>
<th>Challenge</th>
<th>Solution</th>
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</table>
| 1 | **Working Fluid/Material Selections** | **Purdue:**  
- Evaluate working fluids using thermodynamic models  
**UIUC:**  
- Use exp. characterizations to assess fluid kinetics and reversibility |
| 2 | **Designing High Performance Cell**  | **Purdue:**  
- Use ELHP cell test rig to assess the performance  
- Develop a mechanistic ELHP cell model  
**UIUC:**  
- Design, synthesis, and testing of membranes, catalysts, molecules for the electrochemical cell |
| 3 | **Scaling-Up ELHP System**          | **Purdue & UIUC:**  
- Collaborate with Carrier Corp. for developing scaled-up unit |
Impact

• Efficiency metrics for ELHP vs. conventional vapor compression HP:

ELHP operating conditions (cooling mode):
- $T_H = 35 \, ^\circ C$
- $T_L = 10 - 30 \, ^\circ C$
- $T_{SH} = 1 \, ^\circ C$
- $T_{SC} = 0 \, ^\circ C$
- Cell efficiency: 0.6 (-)
- Pump efficiency: 0.7 (-)
- Pinch: 5 K

VC operating conditions:
- $T_H = 35 \, ^\circ C$
- $T_L = 10 - 30 \, ^\circ C$
- $T_{SH} = 1 \, ^\circ C$
- $T_{SC} = 0 \, ^\circ C$
- Overall isentropic efficiency: 0.7 (-)
- Pinch: 5 K

Intrinsic system performance for ELHP outweigh (20 – 30 %) that of vapor compression system
Impact (cont'd)

- **TEA results – Operating Cost:**
  - $3,000 saving @ $\eta_{\text{cell}} = 75\%$, LT = 10 yr

- **TEA results – Capital Cost:**
  - $800$ @ $PV = 10^4$, $A = 1\ \text{m}^2$, LT = 10 yr

Initial TEA shows the cost of ELHP can be economically feasible
Approach

• Goal: Evaluation of ELHP technology

- 2 system models
  - Simplified system model
  - Detailed system model
- 2 cell models
  - Discretized cell model
  - COMSOL cell model
- TEA models

- ELHP cell test rig
  - Working fluid selection
  - Cell performance evaluation
- ELHP system test rig
  - System performance evaluation

Fundamentals
  - thermodynamics
  - heat transfer
  - fluid dynamics
  - controls
  - electrochemistry
  - organic chemistry
  - material science

Analysis Tool
  - system modeling
  - component modeling
  - cost modeling
  - electrochemical characterizations
  - surface topology analysis
  - spectroscopy
  - optimizations
**Progress – (Y1 early-stage): Tasks & Milestones**

1: Project Management
   - **2.1**: Advanced ELHP System Models
     - Provide quantitative list of key EWF requirements

2: Advanced ELHP System Models
   - **2.2**: Advanced ELHP System Models
     - Provide quantitative list of key ESM requirements
   - **3.1**: TEA and Cost Model
     - First version of the complete TEA including estimates of all costs
   - **3.2**: TEA and Cost Model
     - Market discovery
   - **2.3**: Advanced ELHP System Models:
     - Incorporate techno-economic assessment (TEA) in models of the various ELHP-system options
   - **2.4**: Advanced ELHP System Models
     - Down-selection of most promising ELHP system configuration(s) based on complete ELHP system models, including TEA modeling

4: New ELHP EWFs
   - Identify at least one new alternative EWF that meets conventional refrigerant criteria and has three key EWF properties

**Down-selected ELHP: COP improvement of >20% over VC cycles and the projected capital cost of this system enables a simple payback of ≤ 3 years**

**Status of Milestone completion:**
- **Completed**
- **Ongoing this quarter**
Progress - Electrochemical Looping Heat Pump System

- No Vapor Compression
- Possible to run system with zero-GWP working fluid

<table>
<thead>
<tr>
<th>Compound</th>
<th>Reaction Formula</th>
<th>$\Delta T_{\text{bolling}}$ [K]</th>
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<tbody>
<tr>
<td>Isopropanol (Fluid A)</td>
<td>$C_3H_8O$</td>
<td>26.4</td>
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<tr>
<td>Acetone (Fluid B)</td>
<td>$C_3H_6O + H_2$</td>
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James et al. (2019); Kim et al. (2020)
Progress – Milestones for Q1 & Q2 Results (1)

• Provide Qualitative and Quantitative Lists of Key Working Fluid Requirements (EWF):

<table>
<thead>
<tr>
<th>Quantitative Figure of Merits</th>
<th>Qualitative Figure of Merits</th>
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<tbody>
<tr>
<td>$\Delta T_{BP}$ $T_{BP}$</td>
<td>Flammability</td>
</tr>
<tr>
<td>Rate of Reaction (e.g., Current density)</td>
<td>Toxicity</td>
</tr>
<tr>
<td>Reversibility</td>
<td>Environment-friendly EWF</td>
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<tr>
<td>Stability</td>
<td></td>
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<tr>
<td>Cost</td>
<td></td>
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</table>

• Initial Design and Identification of Advanced EWF & ESM:
  • Hydrogenation/Dehydrogenation
  • Electrochemical CO$_2$ Capture and Release

Progress – Milestones for Q1 & Q2 Results (1)

• Provide Quantitative List of Key Working Fluid Requirements (EWF):

  - Thermodynamic Assessment of EWF in terms of reversible voltage
  - Driving force close to 0 V is desirable

- WFs having **high slope** would be desirable for ELHP system
Progress – Milestones for Q1 & Q2 Results (2)

- Provide Quantitative List of Key Working Fluid Requirements (ESM):
  - Reversibility of ELHP ESM for CO₂ refrigerants – **Symmetric shape** is desirable for reversibility & durability

![Diagram showing N₂ Purging and CO₂ Purging with Phenazine examples]

- N₂ Purging:
  - 2 cycles, normal and extended potential windows
  - 20 mV/s
  - N₂ purged (10+ mins)

- CO₂ Purging:
  - Quinoxaline response after
  - 500 mV/s
  - 100 mV/s CO₂ purging
  - 50 mV/s
  - 20 mV/s
Progress – Preliminary Study for Y2

• Upgraded ELHP Cell Test Rig at Herrick Lab.
  – Pioneered by Dr. Nelson James and advanced by Junyoung Kim

Update List:
- Sensor Installations & Calibrations
- Data Acquisition (DAQ)
- Flow Cell Installation
- Two-phase flow Characterizations
- Leak & Pressure Testing
Stakeholder Engagement

- Purdue and UIUC teams have interacted with Carrier Corporation
  - Key contacts: Larry Burns, Hafez Raeisi Farad

- Discuss a future scalability of ELHP system (Y3) with Carrier Corp.

- Regular research meeting with Carrier Corporation
Remaining Project Work (Q3/Q4)

• Demonstration of EWF & ESM Options
  – **Modeling**: evaluate desired thermodynamic properties
  – **Exp.**: evaluate kinetics of working fluids

• Technoeconomic Analysis (TEA):
  – Extend the model developed during Q2
  – Combine TEA with system model
  – Estimate payback period
Thank You

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Made by Junyoung Kim
Project Budget

Project Budget: $1,283,407 (Fed: $999,778; Cost-share: $283,629).
Variances: None.
Cost to Date: Identify what portion of the project budget has been expended to date.
Additional Funding: None.

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<tr>
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<th>FY 2021 (current)</th>
<th>FY 2022 – Nov 30, 2022 (planned)</th>
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## Project Plan and Schedule

<table>
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<tr>
<th>Task</th>
<th>Past Work</th>
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<tbody>
<tr>
<td></td>
<td>Milestone/Deliverable (Originally Planned) use for missed</td>
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<tr>
<td></td>
<td>Milestone/Deliverable (Actual) use when met on time</td>
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<td>FY2021</td>
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<tr>
<td>Task 1: Program Management</td>
<td>Q1 (Dec-Dec)</td>
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<tr>
<td>Task 2: Advanced ELHP System Designs</td>
<td>Q1 (Oct-Dec)</td>
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<tr>
<td>Task 3: Market Transformation</td>
<td>Q4 (Jul-Sep)</td>
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### Past Work

- **Task 1: Program Management**
  - Initial ELHP system models for ESM was developed for Q1
- **Task 2: Advanced ELHP System Designs**
  - ESM demonstration have been done by experiment, not model
- **Task 3: Market Transformation**
  - Developing an advanced ESM model is ongoing task

### Current/Future Work

- **Task 2: Advanced ELHP System Designs**
- **Task 3: Market Transformation**
- **Task 4: New ELHP EWFs**

G/NG