Heat Pump Water Heater Using Solid-State Energy Converters

2016 Building Technologies Office Peer Review

Uttam Ghoshal, ghoshal@sheetak.com
Sheetak Inc.
Project Summary

Timeline:
Start date: 11/15/2012
Planned end date: 5/14/2016

Key Milestones:
1. Development of Bottom Mount 4-Engine Thermoelectric Heat Pump; 5/14/2014
2. Development of High Cooling Power Thermoelectric Modules for Heat Pumps; 5/14/2015
3. Performance (COP > 1.1) and Reliability Thermoelectric Heat Pumps; 6/14/2016

Budget:
Total DOE $ to date: $1,149,900.00
Total future DOE $: $0.00

Target Market/Audience:
Home Water Heaters with Affordable, Reliable Solid-State Heat Pumps

Key Partners:
Whirlpool Appliance (Consultation for Specs)

Project Goal:
Demonstrate a home water heater product with affordable and reliable solid-state heat pumps with COP > 1.1. The project includes development of high cooling power thermoelectric modules as well as development of bottom-mount 4-engine and 8-engine heat pumps.
Purpose and Objectives

Residential Water Heaters

• 15% of energy consumption. 45% are electric heaters: ~ 1.34 Quads of primary energy

• $300- $700 per year energy cost

• Vapor compression based heat pump water heater are very expensive, and limiting in modularity and flexibility

Sheetak’s Solution

Low-Cost Thermoelectric (TE) Heat Pump Water Heater
Impact of the Project

• Demonstration of first TE-based 50 gallon heat pump water heater
• COP >> 1.1 (goal of the SBIR was COP > 1.1)
• High volume manufacturing of thermoelectric coolers and heat pumps for refrigeration and heat pump applications
• Development of novel system-level hardware including self-controllers and fault-tolerant heat-pumps
• Cost-effective modular heat pump water heater
• Achievements
  • COP > 1.5 with modular plug-in thermoelectric engines
  • Long term: Launch of TE based water heater in the market
Original Thermoelectric Heat Pump Water Heater Concept

Thermoelectric Hot Side

Thermoelectric Cold Side (Heat-Pipe Heat Sink)

Inlet cold water

T = 58 °F

TE heat pump

T = T_{TE}

Resistive heater

T = 135 °F

Exit hot water

T_{amb} = 65 °F

Q_{in}
Plug-In Thermoelectric Heat Pump Water Heater

- Modular, scalable, and compatible – addresses needs for capacities 0-100 gallons
- Self controlled loops
- High COP
Water Heater Operation for $I_{\text{TEC}} = 6\text{A}$

Fig. (a) Difference between the 6 Cold Chuck temperatures decreases for $t > 0.9$ hrs.

Fig. (b) Hot Chuck temperatures (for $t < 0.2$ hours, the thermocline in the container prevent hot temperatures from rising)

Fig. (c) Heat pumping decreases as $\Delta T_{\text{TEC}}$ increases (@ $t = 1.3$ hrs $\Delta T_{\text{TEC}} \sim 46^\circ\text{C} - 53^\circ\text{C}$)

Fig. (d) Decrease in heat pumping is indicated as $(T_{\text{cold-outlet}} - T_{\text{cold-inlet}}) \to 0$

Average $(T_{\text{hold-inlet}}, T_{\text{hot-outlet}})$ is indicated by the dotted line.
Water Heater Operation for $I_{TEC} = 3A$

Fig. (a) Difference between the 6 Cold Chuck temperatures decreases for $t > 1.5$ hrs.

Fig. (b) Hot Chuck temperatures are closer to each other as compared to $I_{TEC} = 6A$

Fig. (c) Heat pumping $\rightarrow 0$ 
$\Delta T_{TEC} \rightarrow \Delta T_{\text{max}} (I = 3A)$. After 3 hours, $\Delta T_{TEC} \sim 36^\circ C - 38^\circ C$.

Fig. (d) Decrease in heat pumping is indicated as $(T_{\text{cold-outlet}} - T_{\text{cold-inlet}}) \rightarrow 0$
Average $(T_{\text{hold-inlet}}, T_{\text{hot-outlet}})$ is indicated by the dotted line. $(T_{\text{hot-inlet}} - T_{\text{hot-outlet}}) \sim 2^\circ C$ for $t > 2.5$ hrs
**Measured Coefficient of Performance (COP)**

**$I_{TEC} = 6A$**

Fig. (a) COP based on the rate of rise of average hot water temperature

<table>
<thead>
<tr>
<th>$m$ (kg)</th>
<th>$\delta \Delta T / \delta t$</th>
<th>$Q_{heating}$ (W)</th>
<th>$P_{electric}$ (W)</th>
<th>COP</th>
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<tbody>
<tr>
<td>22.0</td>
<td>0.0076</td>
<td>702</td>
<td>521</td>
<td>1.3</td>
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</table>

Corroborated with COP estimated from $Q_{cooling}$ in Fig. (b).

**$I_{TEC} = 3A$**

Fig. (c) COP estimated from the rate of rise of average hot water temperature

<table>
<thead>
<tr>
<th>$m$ (kg)</th>
<th>$\delta \Delta T / \delta t$</th>
<th>$Q_{heating}$ (W)</th>
<th>$P_{electric}$ (W)</th>
<th>COP</th>
</tr>
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<tbody>
<tr>
<td>22.0</td>
<td>0.0029</td>
<td>268</td>
<td>159</td>
<td>1.7</td>
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</table>

Corroborated with Fig. (d) - COP estimated from $Q_{cooling}$

\[
P_{Fan} + P_{pump} = 26.8W
\]

\[
Q_{cooling} = m_c C_p (T_{OUT} - T_{In})_{Cold}
\]

\[
P_{electric} = I_{TEC} V_{TEC} + P_{Fan} + P_{pump}
\]
Industry-Best Cooling Chips

- Lowest Power Consumption (~½)
- Tunable Cooling Density (1-100 W/cm²)
- High Reliability (MTBF >> 100,000 h)
- High Volume Manufacturing (> 2M pa)

- Flexible–Geometry Complaint
- Enables battery-based portables
- Mechanically robust
- Fault-tolerant

51-Couple 30W TEC
Flexible 30W TEC
Flexible 32-Couple TEC
Disruptive Wafer-Level Processes

<table>
<thead>
<tr>
<th>Ball Milling</th>
<th>SPS</th>
<th>Barrier Metallization/Plating</th>
</tr>
</thead>
</table>

- **Bi, Sb, Te, Se**
- **SPS**
- **Barrier Metallization/Plating**

**TRADITIONAL**

**Larger Batches, Lower Unit Cost**

- Zone Melting Crystal Growth, Dicing Plating
- 1.5 mm thick
- 75 mm
- 0.5 mm thick
- 10× less material
- Traditional
- Sheetak SPS

**Sheetak**
Transformative Assembly Methods

- Multiwire Saw Dicing
- Die Sorting for Tape & Reel
- Automated Pick & Place
- Volumes >>1M
- Highly Automated & Parallel Assembly Lowers Cost and Leverages LED Manufacturing
- Semi-Manual Pick & Place
- Volumes <1M
Progress and Accomplishments

Accomplishments

• Bottom-mount TE heat pump water heaters fabricated and demonstrated
• High volume, high efficiency thermoelectric cooler manufacturing capability for heat pumps established
• Novel modular heat pumps for add-on/plug-in applications demonstrated and tested

Challenges

• Funding for high volume thermoelectric heat pump manufacturing in the US and globally
• Industrial design, controllers for modular fault-tolerant heat pumps with fluid pumps with > 20 years MTBF
Commercialization Strategy

- Initial contacts with Whirlpool in the US and Godrej & Boyce in India
  - Whirlpool for store branded heaters in the US and Asia
  - Godrej and Boyce for developing world markets (India) that focuses on small water capacity

- Commercialization focus for 2016:
  - Leverage beverage refrigeration to manufacture efficient TECs in high volumes and establish revenues
  - Develop industrial designs for plug-in water heater heat pumps and systems for commercialization
  - License system technology for modular heat pumps to water heater appliance manufacturers, and provide volume sourcing of heat pumps
Next Steps and Future Plans

• Become the leader in high volume manufacturing of efficient thermoelectric heat pumps for refrigeration, water cooling and water heating

• Develop self-controllers for modular heat pumps and extend the plug-in capabilities for variety of cooling/heating applications

• Partner with appliance manufacturers for licensing and sales
REFERENCE SLIDES
Project Budget

Project Budget: $1,149,900.00
Variances: None
Cost to Date: $926,897.49
Additional Funding: N/A

Budget History

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<th>11/15/2012–FY2015 (past)</th>
<th>FY2016 (current)</th>
<th>FY2017 (planned)</th>
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<tr>
<td>DOE</td>
<td>Cost-share</td>
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<td>$649,924.57</td>
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# Project Plan and Schedule

### Project Schedule

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<th>Task</th>
<th>FY2014</th>
<th>FY2015</th>
<th>FY2016</th>
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<tr>
<td>Project Start: <strong>May 2014</strong></td>
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<td>Projected End: <strong>May 2016</strong></td>
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<td>Active Task</td>
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<tr>
<td></td>
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<td>(in progress)</td>
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<tr>
<td>Milestone/Deliverable (Originally Planned) use for missed milestones</td>
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<tr>
<td>Milestone/Deliverable (Actual) use when met on time</td>
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<tr>
<td><strong>Past Work</strong></td>
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<tr>
<td>Q1 Product Design</td>
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<td>Q2 Bottom mount TE heat pump design</td>
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<td>Q3 Packaging of Sheetak's Power TE Heat Pumps</td>
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<td>Q4 Multi-module heat pump hardware</td>
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<td><strong>Current/Future Work</strong></td>
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<td>Q5 Preliminary reliability assessment</td>
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<td>Q6 Water heater product prototype assembly</td>
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<td>Q7 Test to water heater standard</td>
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