Heat Pump Water Heater Using Solid-State Energy Converters

2015 Building Technologies Office Peer Review

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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 of 4- and 8-Engine Thermoelectric Heat Pumps; 6/14/2016

Budget:
Total DOE $ to date: $1149900.00
Total future DOE $: $499975.00

Key Partners:
Whirlpool Appliance (Consultation for Specs)

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

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

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)

• Development of novel thermoelectric modules and substrates

• Development of novel system-level hardware

• Cost-effective heat pump water heater

• Achievements
  • Near term: COP > 1 with 4 TE cooling engines
  • Intermediate term: COP > 1.2 with 8 TE cooling engines, teaming with a water heater manufacturer
  • Long term: Launch of TE based water heater in the market
Thermoelectric Heat Pump Water Heater

Inlet cold water

TE heat pump

Resistive heater

Exit hot water

$T_{amb} = 65 \, ^\circ F$

$Q_{in}$

$T = 58 \, ^\circ F$

$T = T_{TE}$

$T = 135 \, ^\circ F$

Thermoelectric Hot Side

Thermoelectric Cold Side (Heat-Pipe Heat Sink)
Preliminary Results: 4 TE Engine Water Heater

- 3GPM water withdrawal in 3 minutes 40 sec (as per testing standards)
- Only TE used for heating after the withdrawal
- Issues: Slow heating observed by TE
Preliminary Results: 4 TE Engine Water Heater

\[ P = mC_p \frac{dT}{dt} + K(T - T_a) \]

\[ \text{COP} = \frac{P}{IV} \]

- \( P = \) heating rate, estimated using the above equation
- Due to discrete measurements and fluctuations in ambient temperature, there are some uncertainties
  - COP is high in the beginning due to low temperature difference
  - COP decreases with time due to increase in temperature difference
  - After a certain temperature rise, resistive heater will be switched on (work on controls, in progress)
High Performance TE Modules – Thin Film Devices

- Very high heat flux > 100 W/cm²
- $\Delta T \sim 50^\circ$C for AlN substrates, COP $\sim 0.6$ for $\Delta T$ (external) = 30°C
- Requires metal-core substrates and high performance solders
- Packaging cost may be high

8-Couple Q&T

Thin Film $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_{3.0}$ and $\text{Bi}_{2}\text{Te}_{2.8}\text{Se}_{0.2}$ Devices

Glass Etching

Metal (Cu/Ni/Au)
TiW/Ta/TaN/TiW
Polyimide
TiW
Glass

Starting 6” glass wafers → Structured substrate → TE wafer → 0.5 x 0.5 mm² dies → Al Modules (∼ 2 x 2 cm²)

U.S. Department of Energy
Energy Efficiency & Renewable Energy
High Performance TE Modules – Substrates

- 150-200 mm Al wafers
- $\Delta T$ (substrate) < 1°C for flux ~ 100W/cm²
- Lower cost than AlN ceramics
- CTE-compatible with heat exchangers

Al Wafer
ALD Alumina
Copper Seed Layers
Patterning
Copper/Ni/Au Plating
Seed Removal and Dicing
High Performance TE Modules – Thick Film Devices

- $\Delta T \sim 80^\circ C$ for Al-core substrates
- Significant performance improvements with proprietary nanostructured materials
- Packaging cost is small for $\sim 1kW$ heat pumps
Progress and Accomplishments

Accomplishments

• Bottom-mount TE heat pump water heater fabricated and preliminary testing data obtained
• Thin film and new thick film TE fabrication process
• Novel metal-core TE substrate developed (superior to state-of-the-art are ceramic substrate)

Challenges

• Slow heating observed by TE heat pump. Risk mitigation involves use of TE heater in conjunction with the resistive heater and better heat sink design
• Significant parasitic temperature losses due to high heat flux in thin film TE. Novel thick film process developed to reduce the parasitic losses
Commercialization Strategy

- Established contacts with Whirlpool and AO Smith in the US and Godrej and Boyce in India
  - AO Smith: World leader in water heaters
  - Whirlpool: Makes store branded heaters
  - Godrej and Boyce: Appliance maker with focus on developing world markets (e.g. India)
  - A.O. Smith is quite cost conscious but Whirlpool and Godrej have stronger interest

- Commercialization focus for the first year:
  - Establish contacts and have introductory discussions

- Commercialization focus for second year:
  - Demonstrate performance of the final prototype with Sheetak TECs (available in the middle of 2nd year)
  - Get into commercial discussions for licensing our system technology and supplying Sheetak TECs
Next Steps and Future Plans

• 8-Engine TE heat pump integration to the water tank

• Development of control algorithm to control TE heat pump and resistive heater operation

• Fabrication of large TE modules on metal-core substrates using Sheetak’s thick film process

• Integrated heat pump modules with Sheetak TE and heat sinks

• Demonstration products for engaging potential electric water heater manufacturers (AO Smith, Godrej and Whirlpool)
REFERENCE SLIDES
# Project Budget

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

## Budget History

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<th>Date</th>
<th>FY2014 (past)</th>
<th>FY2015 (current)</th>
<th>FY2016 – 5/14/2016 (planned)</th>
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# Project Plan and Schedule

## Project Schedule

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<th>FY2016</th>
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<td>Projected End: May 2016</td>
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<td>Past Work</td>
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<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>Current/Future Work</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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- **Completed Work**
- **Active Task (in progress work)**

- **Milestone/Deliverable (Originally Planned)** use for missed milestones
- **Milestone/Deliverable (Actual)** use when met on time

## Timeline

- **Q1** (May-July)
- **Q2** (Aug-Oct)
- **Q3** (Nov-Jan)
- **Q4** (Feb-Apr)
- **Q5** (May-Jul)
- **Q6** (Aug-Oct)
- **Q7** (Nov-Jan)