Molten Salt-Carbon Nanotube Thermal Energy Storage for Concentrating Solar Power Systems

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Overview

Timeline

- March 4, 2009
- December 31, 2011
- 30% complete

Budget

- Total project funding
  - DOE share
    $1,499,986
  - Contractor share
    $375,014
- Funding received in FY09
  $543,472 (DOE)
  $121,517 (cost share)
- Funding for FY10
  $471,543 (DOE)
  $124,970 (cost share)

Barriers

- Barriers addressed
  - Produce a low cost, thermally efficient energy storage system that can dispatch power to meet system peak load

Partners

- Interactions ongoing with DOE labs
- No collaborations at present
- Project lead - Texas Engineering Experiment Station, Texas A&M University
Challenges, Barriers or Problems

• Main challenge is finding a stable mixture of molten salt and nanoparticle that improves thermophysical properties without increasing cost or hazard level
  – Improved specific heat to reduce cost of storage material
  – Improved thermal conductivity to reduce cost of heat exchanger
  – Improved corrosion characteristics to extend life of system

• Improving thermal energy storage capability advances DOE’s goal of reducing the levelized cost of electricity.
Economic Evaluation of Nanofluids for TES-Normalized Results

% Material Cost Increase
- 0
- 10
- 25
- 50

Percent Specific Heat Improvement

TES System Costs [$/kWh-t]
Objective for the project: to create a composite thermal energy storage material using nanoparticles embedded in a molten salt base material, characterize the thermophysical properties of the composite material, and assess the utility of the composite material in a concentrating solar power application.

Objective for 2009: demonstrate feasibility of improving thermal energy storage material thermophysical properties using ~1% nanoparticles

Relevance to Solar Program: increasing specific heat reduces cost of electricity by reducing cost of thermal energy storage (smaller tanks, less material required). Increasing thermal conductivity reduces cost of electricity by reducing the size and cost of heat exchangers. Alternatively, improving thermophysical properties increases revenue by extending operating time further into peak demand hours.
• The title of these slides should make it clear that they count toward your project’s approach!

• Describe overall technical approach:
  – Emphasize unique aspects of your approach and de-emphasize discussion of equipment used;
  – How your research/demonstration/deployment addresses the Program’s technical barriers;
  – How your project is integrated with other research within the Solar Program;
  – Use simple statements so that scientists and engineers, not experts in your area, can readily understand the explanation of your approach.

• Include the planned milestones and go/no-go decisions for FY10 and FY11 and current status towards them.
Approach

Material creation
- examine methods for mixing nanoparticles with base salt (settled on aqueous mixing)
- examine combinations of nanoparticles and base salts (best current combination is carbonate eutectic with silica nanoparticles)
- examine effects of concentration of nanoparticles (work still underway; 1% appears to be close to optimum for spherical nanoparticles, work still underway; 0.1% appears to be close to optimum for nanotubes)

Thermophysical properties measurement
- measure specific heat
- measure thermal conductivity

Stability assessments
- determine corrosion effects on stainless steel (nanoparticles appear to reduce corrosion)
- determine effects of thermal cycling on composite material behavior (work still underway)

System and Economic Modeling
- work just getting started
Approach

Milestones for FY 2010
- Demonstrate long term compatibility (>5000 hours, includes corrosion and thermal cycling) (12/10)
  - Complete initial system analysis (12/10)

Go/No-go criteria for FY 2010
Demonstration of materials that meet the physical and chemical property goals set forth in the FOA or that demonstrate significant advantages versus the state-of-the-art nitrate eutectics will constitute successful completion of Phase 2.

Milestones for FY 2011
- Complete system and economic analysis (12/11)
  - Determine viability of a field demonstration (12/11)

Go/No-go criteria for FY 2011
The major go/no-go decision will be whether or not to proceed to a field demonstration of the technology.
固体相结果

<table>
<thead>
<tr>
<th>材料</th>
<th>平均热容 (J/gK)</th>
<th>标准差 Cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>碳酸盐 (150-300 °C)</td>
<td>1.08</td>
<td>0.1</td>
</tr>
<tr>
<td>碳酸盐 + 1% SiO₂ (150-300 °C)</td>
<td>1.65 (+50)%</td>
<td>0.15</td>
</tr>
<tr>
<td>碳酸盐 (375-440 °C)</td>
<td>1.34</td>
<td>0.05</td>
</tr>
<tr>
<td>碳酸盐 +0.5% SiO₂ (375-440 °C)</td>
<td>1.63 (+6.5%)</td>
<td>0.19</td>
</tr>
<tr>
<td>碳酸盐 + 1% SiO₂ (375-440 °C)</td>
<td>1.64 (+22%)</td>
<td>0.1</td>
</tr>
<tr>
<td>碳酸盐 + 1.5% SiO₂ (375-440 °C)</td>
<td>1.61 (+20%)</td>
<td>0.05</td>
</tr>
<tr>
<td>碳酸盐 + 5% CNT (375-440 °C)</td>
<td>1.40 (+12.4%)</td>
<td>0.1</td>
</tr>
<tr>
<td>碳酸盐 + 添加剂 (375-440 °C)</td>
<td>1.45 (+8%)</td>
<td>0.1</td>
</tr>
<tr>
<td>硝酸盐</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>硝酸盐 + Al₂O₃</td>
<td>1.4 (+8%)</td>
<td>0.1</td>
</tr>
<tr>
<td>氯化物 1</td>
<td>0.83</td>
<td>0.02</td>
</tr>
<tr>
<td>氯化物 1 + 1% SiO₂</td>
<td>0.88 (+6%)</td>
<td>0.035</td>
</tr>
<tr>
<td>氯化物 1 + 添加剂</td>
<td>0.9 - 0.997 (+6-12%)</td>
<td>0.076</td>
</tr>
</tbody>
</table>
### Liquid Phase Results

<table>
<thead>
<tr>
<th>Material</th>
<th>Average Cp</th>
<th>SD Cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate</td>
<td>1.6</td>
<td>0.05</td>
</tr>
<tr>
<td>Carbonate + 1% SiO₂</td>
<td>2.0 (+26%)</td>
<td>0.1</td>
</tr>
<tr>
<td>Carbonate + 1.5% SiO₂</td>
<td>2.8 (+75%)</td>
<td>0.05</td>
</tr>
<tr>
<td>Carbonate + 0.5% SiO₂</td>
<td>1.6 (+2.7%)</td>
<td>0.2</td>
</tr>
<tr>
<td>Carbonate + 5% CNT</td>
<td>2.1 (+20-70%)</td>
<td>0.05</td>
</tr>
<tr>
<td>Carbonate + additive</td>
<td>1.85 (+15-55%)</td>
<td>0.3</td>
</tr>
<tr>
<td>Nitrate</td>
<td>1.55</td>
<td>0.1</td>
</tr>
<tr>
<td>Nitrate + Al₂O₃</td>
<td>1.65 (+6%)</td>
<td>0.5</td>
</tr>
<tr>
<td>Chloride 1</td>
<td>0.84</td>
<td>0.05</td>
</tr>
<tr>
<td>Chloride 1 + 1% SiO₂</td>
<td>0.97 (+15%)</td>
<td>0.05</td>
</tr>
<tr>
<td>Chloride 2</td>
<td>0.97</td>
<td>0.05</td>
</tr>
<tr>
<td>Chloride 2 + 1% SiO₂</td>
<td>1.01 (+4%)</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Findings

- The addition of nanoparticles to base salt results in an increase of \( C_p \) of 10-75%
  - Improvement appears to be independent of properties of nanoparticle
- Based on testing of alumina, titania, and Silica, the largest increase in carbonate \( C_p \) is from Silica
- Based on testing of CNT to base salts results in increase of \( C_p \) of 20-75%
- Surfactant by itself appears to create nanoparticles, increasing carbonate \( C_p \) by 15-55%
- There appears to be an optimum concentration of nanoparticles for increasing \( C_p \)
  - Evaluation of the effect of size of nanoparticles in progress
Findings

• The addition of nanoparticles to base salt results in an increase of thermal conductivity of 35-47%
• The addition of nanoparticles to base salt results in an increase of thermal diffusivity of 25-30%
• Potential 40% costs savings if the 75% specific heat improvement seen in the 1% Hitec/Alumina and 1% Carbonate/Silica nanofluids can be sustained

• Molecular Dynamics (MD) simulations were performed to predict the optimum size and concentration of nanoparticles
• Theoretical framework was developed for designing nanofluids
  – Nanoparticles with low density!
  – Solvent with high density in solid phase!
  – Solvent with high specific heat in solid phase!
Optimization: $C_p$ or $k$?

- Specific heat capacity ($C_p$) enhancement is beneficial for 2-tank storage trough systems (nanoparticle size ~ 10 nm).
- Thermal conductivity enhancement ($k$) is beneficial for heat exchanger performance (nanoparticle size ~ 50 nm).

Thermal Storage Cost Estimates
For NREL Reference Plant
Courtesy of Mr. Craig Turchi, NREL
Conclusions

• Increase in specific heat and thermal conductivity is achievable via the introduction of nanoparticles

• Nitrate nanofluid stability needs to be improved
  – Different nanoparticles
  – pH doping of the Hitec-Solar Salt

• Fabrication technique has a significant effect on thermophysical properties
  – Dispersion of nanoparticles is key
  – Keeping nanoparticles suspended is key
Future Work

• Improve nanofluid stability
  – Nanoparticle size
  – Nanoparticle material
  – Improve dispersion and suspension

• Investigate nano-fin theory
  – Characterize impact on specific heat measurements
  – Develop methods to mitigate effects

• Develop new models for predicting nanofluid specific heat capacity

• Measure changes in thermal conductivity of composites
Future Work

• Continue to investigate impact of nanoparticles on corrosion
• Expand economic analysis of system
  – Multiple operational scenarios
  – Parametric cost assessment
  – Detailed effects of thermal conductivity
• Investigate impact of thermal cycling on nanofluid stability
  – Multiple freeze/thaw cycles
  – Long standing periods while liquid
Future Work

• Additive decomposition may be creating carbon nanospheres
  – Verify improvement in Cp independent of nanotubes
  – Examine applicability to other base materials (low cost nanoparticle creation)

• Investigate fluoride base materials
  – Lower melting point than carbonates
  – Less reactive than nitrates
Future Plans (FY 2011 and beyond)

• FY2010
  – Continue measuring thermophysical properties
  – Begin thermal cycling testing
  – Begin system modeling
  – Continue physical modeling
  – Continue corrosion testing

• FY2011
  – Develop a flow loop test facility
  – Test the optimum configurations of the nanofluids
  – Perform economic feasibility analyses in light of experimental and theoretical results
• No collaborations at this time
• Demonstrated that adding small amounts (~1-1.5%) of nanoparticles to a molten salt increased
  – Specific heat by 75%
  – Thermal conductivity by 47%
  – Corrosion resistance
  – Reduced cost ($/KW-hr) by 40%

• Identified molten salt and nanoparticle combinations that address three major uses in a CSP system
  – Low melting point material (Hitech plus nanoparticles)
  – Trough system PCM (fluoride eutectic plus nanoparticles)
  – Tower system PCM (Hitech or carbonate eutectic plus nanoparticles)