FLEXIBLE COAL POWER PLANT OPERATION WITH THERMAL ENERGY STORAGE UTILIZING THERMOSYPHONS AND CEMENTITIOUS MATERIALS

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# Thermal Energy Storage (TES) using Thermal Batteries

TES was for CSP -- but now a range of applications foresee use of TES

**Spatial** and **Temporal** shifted use of energy -- 270 K to 1,000K

Sensible heat, Latent heat, Thermo-chemical TES

Use Inexpensive, Widely available Well characterized Materials for TES

<table>
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<tr>
<th>Energy Stored</th>
<th>Use of Energy</th>
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<tr>
<td>Coal Boiler Steam / HTF</td>
<td>Steam, sCO₂ ORC Electricity</td>
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<td>Gas Turbine Enthalpy units</td>
<td>Process Heat with Steam / HTF</td>
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<td>CSP Steam</td>
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<td>CSP HTF</td>
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<td>Electricity – Off-Peak, Solar PV, Wind</td>
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<td>Nuclear Plant – Steam, Off-Peak Electricity</td>
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<td>Cold Energy from Cold Nights / Other</td>
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Temporal & Spatial shift Applications of Thermal Batteries

Thermal Battery

- Concentrated Solar
- Solar PV / Wind
- Off Peak Electricity
- Nuclear Reactor
- Natural Gas HRSG
- Coal Boiler

Energy Sources

- Electricity
- Steam/sCO$_2$/ORC Turbine
- Flue Gas
- Heat Transfer Fluid

Applications

- Heat Transported to Application site
- Process Heat Replace steam
- HVAC
- Chemical Processing
- Replace steam

Electricity to Grid
Project Objectives – Flexible Coal Plant Operation with TES

• TES Thermal Battery Concept and Related Challenges:
  • Coal power plants have been base load units
  • With TES, fossil plants could be flexible & deliver power to meet today’s and future grid challenges

• Cementitious Materials for TES:
  • Cementitious materials - Inexpensive, Well characterized but poor conductors
  • Thermosyphons have good ‘conductivity’ – improve energy & power transfer.
  • Integrate system with plant operating conditions – for better plant response.

• Design Goals:
  • Operating temperature up to 400°C
  • Round-trip efficiency ~ 90%
  • Cost < $25/kWh(th)
Overall Project objectives:

- Engineer **concrete matrix** for improved thermal/mechanical properties for TES concept at rated temperature.
- Develop and adapt **thermosyphon** technology into the TES in Cementitious media
- Engineer and optimize **heat transfer** in concrete and to fluids.
- Integration of the TES concept with a coal-fired **power plant**, including thermal cyclic response.
- Perform **techno-economic** analysis of the TCM-TES system.
Lehigh Thermal Battery Cells (Lehigh TBC)

- Lehigh Thermal Battery Cell (TBC) is a device enabling TES
- Lehigh TBC houses and encloses storage media and transport phenomenon
- In one design, the Lehigh TBC encloses concrete and thermosyphons
- Provide for user/plant fluid flow to/from TBC for TES
- Designs based on TES Temp., operating pressure, energy storage (MWh), and power (MW).
Thermal Reactions of Chemical Compounds in Hydrated Concrete

- Free surface water removal before 110°C
- CSH gel (CaO·SiO$_2$·H$_2$O) progressively dehydrate from 110°C to 400°C
- Calcium Hydroxide (Ca(OH)$_2$) decomposed from 450°C to 500°C

Limiting the temperatures at which concrete can be effectively used for TES
Thermal Stress Behavior of Concretes for TES

- Thermal demands result in varied stress distributions in TES during charging and discharging.
- The Lehigh Concrete TES System is designed to minimize plastic response during operation.
Thermal Conductivity and Specific Heats of Concretes

Specific Heat of Concretes Developed are 1.4 to 1.6 here vs. NEST (1 to 1.2) and DLR (0.9 to 1.0) kJ/kg-K
Thermal conductivity 1.88 W/m-K is about the same
Energy Into/Out of – Charging and Discharging of Concrete

- Sensible Heat Storage and Retrieval as a function of $k$, Delta T, Mass, Cp, ID, OD
- Capacity kJ $\rightarrow$ mass and Cp, Delta T
- Large Volumes $\rightarrow$ Large Capacity $\rightarrow$ May never reach desired Temperatures
- Rate of Energy $\sim$ Power $\rightarrow$ Characteristic Distance and $k$
- More economical larger Concrete modules will be slower in response for in/out.
Energy Transport in Concrete – Effect of Multiple Pipes

- Effect of Multiple Thermosyphons to Distribute Energy
- More Thermosyphons in effect decrease the characteristic length for heat transfer in concrete
- Comparison with NEST work
  - NEST used 4 Steam in Pipes inside Concrete
  - Lehigh TBC use 7 Thermosyphons to Distribute Energy in Concrete
Thermosyphon Flooding Limit Behavior

Establish the heat transfer limits of the 1” Thermosyphon

- Heated with Electrical Cartridge Heaters -- Aluminum heater block (bottom)
- Aluminum Cooling block (top) with Air Flow

Power Rating for Energy Transported for 1” TS

Q = 1,060 W
Hybrid Thermosyphon

Hybrid thermosyphon -- Used for Charging and Discharging the TBC

- Requires fewer thermosyphons
- Enhance thermal performance

Air cooling

Energy In

Energy Out
Hybrid Thermosyphon Performance – Discharge Mode

Power Out: ~1260W
Thermosyphon - Concrete TES Charging with Electrical Energy
Thermosyphon - Concrete TES Charging with Electrical Energy
Energy Input to/from Lehigh TBC to/from Coal Power Plant

Charging - Energy into TES - Options for a 580 MWe Unit
Energy Input to/from Lehigh TBC to/from Coal Power Plant

Potential TES Charge Option

• Before TES: Superheated vapor at 403 C, 1,071 psia, extracted from high pressure turbine stage 1 (T-HP1).

• After TES: Steam at 286 C and 1,021 psia and 10 % quality is mixed with superheated steam at 342 C and 711 psia from high-pressure turbine stage 2 (T-HP2) and sent to the cold re heater.

• TES power input = 16.67 MW(th).

• Charging will take place at 16.67 MW(th) for 6 hours. Total energy stored is 100 MW(th)h.

• Charging process will incur in an increment in total coal mass flow to maintain cold reheat setpoint.

• Steam mass flow through TES is 76,078 lb/h which represents 2 % of the total mass flow extraction of the T-HP1 and 3 % of the mass flow extraction of the T-HP2.
Potential **TES Discharge Option**

- **Before TES:** Steam at 266°C, 746 psia and 10% quality extracted from feed water heater No. 7 (FWH7).

- **After TES:** Superheated vapor at 400°C and 711 psia (after TES) is mixed with superheated steam at 342°C and 711 psia from high-pressure turbine stage 2 (T-HP2) and sent to the reheater and sent to the cold reheat.

- **Discharging cycle starts with 40 MWth and the power is reduced by 10 MWth linearly for 4 hours. Total discharged energy is 100 MWhth.**

- **Power output is increased from 580 MWe to 592 MWe during the first hour.**

- **Steam mass flow through TES is 169,655 lb/h which represents 60% of the total mass flow leaving the FWH7 and 6% of the mass flow from T-HP2.**

- **The boiler is running at 100% of steam production (3,520,088 lb/h) and the coal mass flow is reduced from 388,445 lb/h to 387,491 lb/h due to the temperature increase in cold reheat.**
Summary – Lehigh Thermal Battery Cells (TBC) Design

- Thermosyphon design for Lehigh TBC – Performance tests for Hybrid thermosyphon.
- Choice of Concrete and Property determination for use in Lehigh TBC – Better TES performance than other data reported in the literature.
- Numerical modeling – COMSOL and FLUENT - Design of concrete modules for Lehigh TBC.
- Thermal tests for Concrete + Thermosyphon to prove charging of a Lehigh TBC.
- ASPEN Analysis for potential Charging and Discharging of Lehigh TBC for a Coal Power Plant.
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