Thermal Energy Storage

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Introduction

- Energy storage (ES) has only recently developed to a point where it can have a significant impact on modern technology
- ES is critically important to the success of any intermittent energy source in meeting demand
- For example, the need for storage for solar energy applications is severe, especially when the solar availability is lowest, in winter
Introduction

• ES systems can contribute significantly to meeting society’s need for more efficient, environmentally benign energy use in building heating and cooling, aerospace power, and utility applications

Introduction

• The use of ES systems often result in such significant benefits as:
  – Reduced energy costs
  – Reduced energy consumption
  – Improved indoor air quality
  – Increased flexibility of operation
  – Reduced initial and maintenance costs
Energy storage methods

• A large variety of ES techniques are under development, which can be grouped as follows:
  – Mechanical
  – Thermal
  – Chemical
  – Biological
  – Magnetic

Energy storage methods

• Thermal energy storage
  – Thermal energy may be stored by:
    • Elevating or lowering the temperature of a substance (i.e. altering its sensible heat)
    • Changing the phase of a substance (i.e. altering its latent heat)
    • A combination of the two
  – TES is the temporary storage of high- or low-temperature energy for later use
Energy storage methods

• Thermal energy storage
  – TES offers the possibility of storing energy before its conversion to electricity
  – Energy quality as measured by the temperatures of the materials entering, leaving and stored within a storage is an important consideration for TES

Thermal energy storage methods

• Basic principle of TES
  – Energy is supplied to a storage system for removal and use at a later time
  – What mainly varies is the scale of the storage and the storage method used
  – Seasonal storage requires immense storage capacity
Thermal energy storage methods

• Basic principle of TES
  – A complete storage process involves at least three steps: charging, storing and discharging

  ![Diagram of TES process]

  - Charging
  - Storing
  - Discharging

• In terms of storage media, a wide variety of choices exists depending on the temperature range and application

  – For sensible heat storage:
    • Water is a common choice because it has one of the highest specific heats of any liquid at ambient temperatures
    • Solids have the advantage of higher specific heat capacities, which allow for more compact storage units
Basic thermodynamics

- Heat storage as sensible heat
  - solids (stone, brick,...)
  - liquids (water, ...)

\[ \Delta Q = m \cdot c \cdot \Delta T \]

The most common method for heat storage

- Heat storage as latent heat
  - melting at constant pressure
    \[ \Rightarrow \text{small volume change} \]
    \[ \Rightarrow \text{no temperature change} \]

Materials with useful phase change
- latent heat storage material,
- phase change material (PCM)
Basic thermodynamics

- Heat storage as latent heat
  - PCM can store about 3 to 4 times more heat per volume than is stored as sensible heat in solids or liquids, in a $\Delta T$ of 20 ºC

Potential applications

1. Stabilization of temperatures
   $\Rightarrow$ buildings, transport boxes, ...
2. Storage of heat or cold
   - at small temperature changes
   - with high storage density
   $\Rightarrow$ domestic heating, ...
Basic thermodynamics

<table>
<thead>
<tr>
<th></th>
<th>kJ/L</th>
<th>kJ/kg</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>sensible heat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>granite</td>
<td>50</td>
<td>17</td>
<td>ΔT=20°C</td>
</tr>
<tr>
<td>water</td>
<td>84</td>
<td>84</td>
<td>ΔT=20°C</td>
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<tr>
<td>latent heat</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ice</td>
<td>300</td>
<td>330</td>
<td>0°C</td>
</tr>
<tr>
<td>paraffin</td>
<td>180</td>
<td>200</td>
<td>5°C to 130°C</td>
</tr>
<tr>
<td>saltpolyhydrite</td>
<td>300</td>
<td>200</td>
<td>5°C to 130°C</td>
</tr>
<tr>
<td>salt</td>
<td>600 - 1500</td>
<td>300 - 700</td>
<td>300°C to 800°C</td>
</tr>
<tr>
<td>chemical energy</td>
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<td></td>
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<tr>
<td>H gas</td>
<td>11</td>
<td>120000</td>
<td>300K, 1bar</td>
</tr>
<tr>
<td>H gas</td>
<td>2160</td>
<td>120000</td>
<td>300K, 200bar</td>
</tr>
<tr>
<td>H liquid</td>
<td>8400</td>
<td>120000</td>
<td>20K, 1bar</td>
</tr>
<tr>
<td>gas (petroleum)</td>
<td>33000</td>
<td>44600</td>
<td></td>
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<tr>
<td>electrical energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>battery</td>
<td>200</td>
<td>zinc/manganeseoxide</td>
<td></td>
</tr>
</tbody>
</table>

Classes of materials

- Carbonates
- Fluorides
- Chlorides
- Fatty acids
- Paraffines
- Melting temperature [°C] melting enthalpy [kJ/L]

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Building Integration of Solar Thermal Systems – TU1205 – BISTS

Physical and technical requirements

**Physical:**
- Suitable phase change temperature
- Large $\Delta H$ and $c_p$
- Large thermal conductivity
- Reproducible phase change
- Little subcooling

**Technical:**
- Low vapor pressure
- Small volume change
- Chemical and physical stability
- Compatibility with other materials

**Economical:**
- Low price
- Non toxic
- Recyclable

Building applications

- Passive systems in the envelope
- Active systems in the envelope (ventilated façade)
- DHW solar energy with PCM in water tank
- Heat pump with PCM for daily storage
Passive building applications

- To increase the thermal inertia of the building
- Practical assessment of the influence of PCM integrated in building structures and their influence on thermal stability of indoor environment
- In order to assess the impact of the solutions adopted, monitoring is necessary
Passive building applications

- University of Lleida
  - Different cubicles were built using different Mediterranean typical constructive solutions. Internal dimensions are 2.4x2.4x2.4 meters
  - Typical Spanish continental climate, with cold winters and warm and relatively dry summers

- The **important temperature oscillations** during day and night make it very suitable for the PCM operation (melting during the day and solidifying during the night)
Passive building applications

• University of Lleida
  – The PCMs tested were designed for cooling applications
    • Reference cubicle without insulation and without PCM
    • Experimental cubicle without insulation and with microencapsulated PCM
Passive building applications

- Instrumentation
  - Heat flux sensor
  - Temperature sensors (PT 100)
  - Piranometer
  - Meteorological station
  - Internal ambient temperature and humidity
  - Energy consumption

Passive building applications

- Envelope with macroencapsulated PCM
  - Experimental set-up:
    - Small house-shaped cubicles
    - Different constructive solutions:
      - Concrete
        - No insulation
        - w/wo microencapsulated PCM
      - Conventional brick
        - No insulation
        - Different insulation materials
      - Alveolar brick
        - No insulation
        - w/wo macroencapsulated PCM
Passive building applications

- Concrete envelope with microencapsulated PCM
  - PCM MICRONAL®PCM (BASF)
    - 26°C melting temperature
    - Phase change enthalpy of 110 kJ/kg
    - Each panel incorporates around 5% in weight
  - No insulation
  - Windows → south, east and west walls
Passive building applications

- Concrete envelope with microencapsulated PCM

Outdoors temperature and temperatures of the west wall, July 2005

Consumption:
- 2ºC
- 3ºC
- 26ºC

- University of Lleida (Spain)
  - Brick cubicles
    - Reference cubicle (Reference): This cubicle has no insulation
    - Polyurethane cubicle (PU): 5 cm of spray foam polyurethane as insulation
    - PCM cubicle (RT27+PU): 5 cm of spray foam polyurethane as insulation and an additional layer of PCM
      - CSM panels containing RT-27 paraffin are located between the perforated bricks and the polyurethane
Passive building applications

- University of Lleida (Spain)
  - Alveolar brick cubicles
    - Reference cubicle (Alveolar): The alveolar brick has a special design which provides both thermal and acoustic insulation. No additional insulation was used in this cubicle
    - PCM cubicle (SP25+Alveolar): Several CSM panels containing SP-25 A8 hydrate salt are located inside the cubicle, between the alveolar brick and the plaster
Passive building applications

- Brick envelope with macroencapsulated PCM
  - Conventional brick:
    - **Reference**: No insulation
    - **Polyurethane**: 5 cm of polyurethane
  - **RT27+PU**: CSM panels (RT-27) and 5 cm of polyurethane

<table>
<thead>
<tr>
<th>Paraffin RT-27</th>
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</thead>
<tbody>
<tr>
<td>Melting point (°C)</td>
</tr>
<tr>
<td>Congealing point (°C)</td>
</tr>
<tr>
<td>Heat Storage Capacity (kJ/kg)</td>
</tr>
<tr>
<td>Heat conductivity (W/m·K)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>28</td>
</tr>
<tr>
<td>26</td>
</tr>
<tr>
<td>179</td>
</tr>
<tr>
<td>0.2</td>
</tr>
</tbody>
</table>

- Brick envelope with macroencapsulated PCM
  - Alveolar brick:
    - **Alveolar**: No insulation
    - **SP25+Alveolar**: CSM panels (SP-25 A8) inside the cubicle

<table>
<thead>
<tr>
<th>Hydrated salt SP-25 A8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point (°C)</td>
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<tr>
<td>Congealing point (°C)</td>
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<tr>
<td>Heat Storage Capacity (kJ/kg)</td>
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<td></td>
</tr>
<tr>
<td>26</td>
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<tr>
<td>25</td>
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<tr>
<td>180</td>
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</table>
Passive building applications

- Brick envelope with macroencapsulated PCM. Free-floating experiments

Outside temperatures swing:
18-36 °C
Solar radiation: 900 W/m² every day

CONVENTIONAL BRICK
Summer period – 04/08/08 to 07/08/08

<table>
<thead>
<tr>
<th>Date</th>
<th>Temperature (ºC) Inside Reference</th>
<th>Temperature (ºC) Inside PU</th>
<th>Temperature (ºC) Inside RT27+PU</th>
<th>RT-27 Phase Change Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/08/08</td>
<td>30.5</td>
<td>29.5</td>
<td>29</td>
<td>2.9ºC</td>
</tr>
<tr>
<td>05/08/08</td>
<td>30</td>
<td>29.5</td>
<td>29.5</td>
<td>1ºC</td>
</tr>
<tr>
<td>06/08/08</td>
<td>30</td>
<td>29.5</td>
<td>29.5</td>
<td>1ºC</td>
</tr>
<tr>
<td>07/08/08</td>
<td>30</td>
<td>29.5</td>
<td>29.5</td>
<td>1ºC</td>
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</tbody>
</table>

ALVEOLAR BRICK
Summer period – 02/08/08 to 04/08/08

<table>
<thead>
<tr>
<th>Date</th>
<th>Temperature (ºC) Inside Alveolar</th>
<th>Temperature (ºC) Inside SP25+Alveolar</th>
<th>SP-25 A8 Phase Change Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>02/08/08</td>
<td>30.5</td>
<td>29.5</td>
<td>0.9ºC</td>
</tr>
<tr>
<td>03/08/08</td>
<td>30.5</td>
<td>29.5</td>
<td>0.9ºC</td>
</tr>
<tr>
<td>04/08/08</td>
<td>30.5</td>
<td>29.5</td>
<td>0.9ºC</td>
</tr>
</tbody>
</table>
Passive building applications

• Brick envelope with macroencapsulated PCM. Controlled temperature experiments
  – Different experiments done in controlled temperature mode
    Summer period: June - August
    Set point @ 24 °C
  – The weather conditions were ideal for the PCM operation
    Outside temperatures swing: 12-35 °C
    Solar radiation: 800-900 W/m² during all days

Energy consumption
Set point @ 24 °C
Passive building applications

- Brick envelope with macroencapsulated PCM.

Controlled temperature experiments

<table>
<thead>
<tr>
<th>Energy Consumption (Wh)</th>
<th>Energy Savings (Wh)</th>
<th>Energy Savings (%)</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>9376</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PU</td>
<td>4583</td>
<td>4703</td>
<td>51.12</td>
</tr>
<tr>
<td>RT27+PU</td>
<td>3907</td>
<td>5469</td>
<td>58.33</td>
</tr>
<tr>
<td>Alveolar</td>
<td>5053</td>
<td>4323</td>
<td>46.11</td>
</tr>
<tr>
<td>SP25+Alveolar</td>
<td>4188</td>
<td>5188</td>
<td>55.33</td>
</tr>
</tbody>
</table>

1 Set point of 24 °C during 5 days
2 Referred to the Reference cubicle
3 Referred to the cubicle with analogue constructive solution and without PCM

Conclusions

- Free floating
  - Reduction of the maximum and minimum peaks during the warm season
  - Reduction of the temperature oscillation (up to 1 °C)
  - Delay on the heat flux entering through the inside wall (3-8 hours)
Passive building applications

• Brick envelope with macroencapsulated PCM.

Conclusions

– Controlled temperature
  • Important effect of the set point
  • Moderate set point (24 ºC) → **Important energy savings** (about 15%)

Active system in the envelop

• Ventilated Double Skin Facade with PCM
  – Reference and ventilated facade cubicles
Active system in the envelop

• Programmable door openings and fans

• Operation in free floating conditions
Active system in the envelop

- Operation with heat pump at 21 °C

DHW solar energy with PCM

- Solar Thermal Systems: Use of Phase Change Materials (PCM) for the improvement of energy storage in solar water heating systems
  - To investigate the potential of hot water storage tank size reduction by introducing PCM
  - To increase of storage capacity of the system

Increase cost effectiveness of the system
DHW solar energy with PCM

- PCM modules are introduced in the (top) hot water storage tank and the system is tested under conditions that mimic real-life operation.
DHW solar energy with PCM

• PCM
  – Granular compound of 90 vol.% of sodium acetate trihydrate and 10 vol.% graphite (commercial) → heat transfer improvement
  – Encapsulation used was commercial aluminium bottles 8.8 cm of diameter and 31.5 cm height, capacity 1.5 L

• Description of the installation
  – 2 thermal solar collectors
  – 2 storage water tanks of 146 L
  – Electrical heater outside the tanks
  – Installation automatically controlled
  – Different PCM modules located at the upper part of the storage tank
DHW solar energy with PCM

- Instrumentation
  - Water temperature at 0, 30, 90, 110 and 120 cm from the bottom of the tank
  - Ambient temperature
  - Inlet and outlet water temperature
  - PCM temperature inside the modules
  - Water mass flow

- University of Lleida
  - Experiments with 2, 4 and 6 modules
    - Cooling down, reheating: water heated up to 80 °C
    - Solar operation
DHW solar energy with PCM

• University of Lleida

<table>
<thead>
<tr>
<th>Nº modules</th>
<th>PCM mass (kg)</th>
<th>IPF (%)</th>
<th>Energy density increase (%) ($\Delta T = 1, K$)</th>
<th>Energy density increase (%) ($\Delta T = 8, K$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.1</td>
<td>2.05</td>
<td>40</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>4.2</td>
<td>4.1</td>
<td>57.2</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>6.3</td>
<td>6.16</td>
<td>66.7</td>
<td>16.4</td>
</tr>
</tbody>
</table>

IPF: PCM volume/tank volume
DHW solar energy with PCM

- University of Lleida
  - Cooling down experiments with 2 and 6 modules:
    - The top water layer in contact with the PCM modules kept the temperature around 54-55 °C between 7-9 hours

Extra time with hot water at 36-38 °C ≈ 50 min

Theoretical compensation temperature about 10 °C (from 27 °C to 37 °C)
DHW solar energy with PCM

- University of Lleida
  - Reheating experiments also with 2 and 6 modules:
    - The time with water at a **useful temperature** highly **depends** on the amount of PCM
    - A **theoretical compensation temperature** of:
      - About 5°C during **30 minutes** (29°C to 34°C) (2 modules)
      - About 10°C during **50 minutes** (27°C to 37°C) (6 modules)

![Graph showing temperature and radiation over time](image-url)
DHW solar energy with PCM

- University of Lleida
  - Experiments with solar collectors were carried out for 4 and 6 modules
    - No significant differences were observed

Heat pump with PCM for daily storage

- Development of thermal storage applications for HVAC solutions based on Phase Change Materials
  - TES system is integrated to a HVAC system
  - PCM thermal energy storage units are used to reduce the energy consumption
  - The objective is to take advantage of the low electricity night tariff:
    - The PCM is charged at night and discharged during the day
Heat pump with PCM for daily storage

- PCM thermal energy storage units
  - Two PCM units are coupled to a heat pump and an AHU

<table>
<thead>
<tr>
<th>Tank</th>
<th>PCM</th>
<th>Melting temperature</th>
<th>Melting enthalpy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold TES tank</td>
<td>510</td>
<td>10 °C</td>
<td>155 kJ/kg</td>
</tr>
<tr>
<td>Hot TES tank</td>
<td>546</td>
<td>46 °C</td>
<td>210 kJ/kg</td>
</tr>
</tbody>
</table>

12 flat slabs in 2 columns
Heat pump with PCM for daily storage

• The prototype will be tested in Spanish summer and Estonian winter conditions in a 3x3x3 m cubicle
Heat pump with PCM for daily storage

• Results for space heating experiments

From 09:00 h:
- Water tank: 247 min
- PCM tank: 298 min + 51 min

Thank you for your attention

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