Phase Change Materials (PCMs) for energy storage in Thermal Solar Cooling Systems

Andrea Frazzica
Valeria Palomba
Vincenza Brancato
✓ Introduction
✓ Latent Thermal Energy Storage
✓ Example of latent TES for solar cooling
✓ PCMs for solar cooling applications
✓ Design and testing of latent TES @ ITAE
✓ Conclusions and future perspectives
INTRODUCTION

Why do we need a TES?

Main functions

- Supply-demand matching
- Peak shaving
- Flexibility

Main parameters

- Quality [°C]
- Capacity [GJ]
- Storage density [GJ/m³] / [kJ/kg]
- Power [kW]

Field of application of thermal storage
INTRODUCTION

**TES in solar cooling systems**

- **HT** 180 – 80 °C
- **MT** 40 – 30 °C
- **LT** 15 – 5 °C

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**INTRODUCTION**

**TES technologies**

**Sensible heat**
- Heat capacity of materials
- Water, solids (e.g. concrete, rocks)

**Latent heat**
- Phase change
- Water, organic and inorganic PCMs

**Thermo-Chemical heat**
- Physical or chemical bonds
- Adsorption, absorption, chemical reactions
Key points:

- Working temperature interval
- Latent and Specific Heat of PCM
Realization and testing of a latent heat storage supporting the heat rejection of an absorption chiller

1. Dry cooler+latent TES can substitute the wet cooling tower
2. Increased absorption chiller performance allows to reduces the over-sizing of the solar collector system.
3. Latent TES power of 10 kW and storage capacity of 120 kWh has proven the feasibility of the storage concept.
4. Positive effect on the SEER (including winter operation) and high system reliability (more than 800 cycles performed)

## Literature survey

<table>
<thead>
<tr>
<th>Material</th>
<th>( T_m ) [°C]</th>
<th>Latent Heat [kJ/kg]</th>
<th>Density [g/cm(^3)]</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )-Naphthol (99%) Sigma-Aldrich*</td>
<td>96</td>
<td>163</td>
<td>N.A.</td>
<td></td>
</tr>
<tr>
<td>Xylitol (99%) Sigma-Aldrich*</td>
<td>94</td>
<td>263.3</td>
<td>N.A.</td>
<td></td>
</tr>
<tr>
<td>D – Sorbitol (98%) Sigma-Aldrich*</td>
<td>97</td>
<td>185</td>
<td>N.A.</td>
<td></td>
</tr>
<tr>
<td>Acetamide (-99%) Sigma-Aldrich*</td>
<td>81</td>
<td>241</td>
<td>1.159</td>
<td></td>
</tr>
<tr>
<td>( \text{KAl(SO}_4\text{)}_2\cdot12\text{H}_2\text{O} ) (98%) Sigma-Aldrich* (CODE: APSD)</td>
<td>91</td>
<td>184</td>
<td>N.A.</td>
<td></td>
</tr>
<tr>
<td>( (\text{NH}_4)\text{Al(SO}_4\text{)}_2\cdot12\text{H}_2\text{O} ) (99%) Sigma-Aldrich* (CODE:AASD)</td>
<td>95</td>
<td>269</td>
<td>1.640</td>
<td></td>
</tr>
</tbody>
</table>

### Pure Chemicals

#### Organics

<table>
<thead>
<tr>
<th>Material</th>
<th>( T_m ) [°C]</th>
<th>Latent Heat [kJ/kg]</th>
<th>Density [g/cm(^3)]</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plus-ICE A82 PCM products*</td>
<td>82</td>
<td>155</td>
<td>0.850</td>
<td></td>
</tr>
<tr>
<td>Plus-ICE S83 PCM products*</td>
<td>83</td>
<td>141</td>
<td>1.600</td>
<td></td>
</tr>
<tr>
<td>Plus-ICE S89 PCM products*</td>
<td>89</td>
<td>151</td>
<td>1.550</td>
<td></td>
</tr>
</tbody>
</table>

### Commercial PCMs

- **Organics**
  - Plus-ICE A82 PCM products*
  - Plus-ICE S83 PCM products*
  - Plus-ICE S89 PCM products*

**Latent TES design: finned tubes**

**Tube:**
- 1D model
- Developed fluid flow
- Radial thermal gradient negligible
- Nu-correlation for heat transfer between tube and fluid

**Fin and PCM:**
- 3D model
- Half a fin and half a fin gap with PCM
- Convection in liquid state of the PCM is negligible
- Volumetric expansion of the PCM during phase change is neglected

Coupling by heat flow and temperature at inner tube wall
Latent TES design: finned tubes

1D Model

\[ \dfrac{d}{dt} \rho C_p \Delta T + \lambda A_c \nabla \Delta T = Q \]

Boundary Conditions

\[ \dot{q} = 0 \]

FROM MEASUREMENTS

3D Model

\[ \rho C_p \dfrac{\partial T}{\partial t} + \rho C_p u \nabla T + \nabla (-k \nabla T) = Q \]

Boundary Conditions

Coupling of 3D and 1D Model

\[ \dot{q}_{\text{tube}} = h(T_{\text{fluid}} - T_{\text{wall}}) \]

\[ \dot{q}_{\text{fin}} = \dot{q}_{\text{tube}} \times f \]

\[ f = \dfrac{A_{\text{corresponding}}}{\text{areas in 3D and 1D model}} \]

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Latent TES design: finned tubes

FIN-AND-TUBES HEX

- AISI 416L
- 48 FINS x 5 mm gap
- 4 ranks
- 400x650x350mm
- 38 kg PCM

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DESIGN AND TESTING OF LATENT TES @ ITAE

Testing rig

- Simulation of realistic working boundaries
- Fully automatic operation (charging/discharging)
- Max heating power 24 kW
Testing conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STATIC TESTS</strong></td>
<td></td>
<td><strong>DISCHARGE</strong></td>
<td></td>
</tr>
<tr>
<td>Flow rate [kg/min]</td>
<td>5, 10, 13.5, 17.5, 20</td>
<td>Flow rate [kg/min]</td>
<td>3.5, 5, 10, 13.5, 17.5, 20</td>
</tr>
<tr>
<td>Initial temperature [°C]</td>
<td>20, 25, 30, 45, 50, 55, 65, 75</td>
<td>Initial temperature [°C]</td>
<td>83, 85, 86, 88, 90, 92</td>
</tr>
<tr>
<td>Final temperature [°C]</td>
<td>85, 88, 90, 92</td>
<td>Inlet temperature [°C]</td>
<td>65, 70, 75</td>
</tr>
<tr>
<td>Inlet temperature [°C]</td>
<td>85, 90, 94</td>
<td>ΔT_{0-fin} [°C]</td>
<td>7, 12, 15, 20</td>
</tr>
<tr>
<td><strong>DYNAMIC TESTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge/discharge time [min]</td>
<td>10, 15, 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate [kg/min]</td>
<td>10, 20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Measured parameters

Charge/discharge energy: $$E = \int_{0}^{\tau_{\text{fin}}} m c_p (T_{\text{in}} - T_{\text{out}}) \cdot d\tau$$

Average charge/discharge power: $$P_{\text{ave}} = \frac{\int_{0}^{\tau_{\text{fin}}} m c_p (T_{\text{in}} - T_{\text{out}}) \cdot d\tau}{\tau_{\text{fin}}}$$

Charge/discharge efficiency:

$$\varepsilon_{\text{ch}} = \frac{E_{\text{th, ch}}}{E}$$

$$\varepsilon_{\text{disch}} = \frac{E}{E_{\text{th, disch}}}$$
Static tests: charging
Static tests: discharging
**Dynamic tests**

**Effect of the varied parameters**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VARIATION RANGE</th>
<th>POWER</th>
<th>ENERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CHARGE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate</td>
<td>3.5 – 20 kg/min</td>
<td>60%</td>
<td>20%</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>90°C – 96 °C</td>
<td>30%</td>
<td>13%</td>
</tr>
<tr>
<td><strong>DISCHARGE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate</td>
<td>5 – 21 kg/min</td>
<td>40%</td>
<td>-10%</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>65°C – 75 °C</td>
<td>-80%</td>
<td>-20%</td>
</tr>
<tr>
<td>ΔT initial-final</td>
<td>7.5 - 20 °C</td>
<td>120%</td>
<td>10%</td>
</tr>
</tbody>
</table>

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CONCLUSIONS ...

✓ Latent TES can represent a viable solution to increase the compactness of TES for solar cooling applications

✓ A TES density 50% higher than sensible water-based systems have been achieved for a finned-tubes latent TES designed, realized and tested @ ITAE labs

✓ Discharging efficiencies up to 60% over theoretical ones have been measured

✓ Still, low heat transfer efficiencies and low power densities have been achieved
... AND FUTURE ACTIVITIES

✓ Second generation of latent TES for solar cooling applications, with higher heat transfer efficiency, realized and tested in lab

✓ Test of other classes of PCMs (e.g. hydrated salts) and proper additives to increase thermal conductivity

✓ Field test in small scale solar cooling plant, to verify the performance under real working boundaries

✓ Extension of the activity towards solar cooling systems driven by concentrating solar collectors (T>120°C)
Thank you

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