Phase Change Materials for thermal energy storage

Integrated into process heating and cooling applications

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Introduction

- Phase change Materials can store heat within a narrow temperature range;

- Proven technology, less denser than thermochemical heat storage;
Research Aim

• Design, develop and test a 10kWh latent heat storage prototype to integrate domestic space heating networks backed by a heat pump;

• Design and optimize latent heat storage containers to integrate centralized ventilated air conditioning systems backed up by heat pumps and solar thermal;

• Design and develop a latent heat storage system to meet daily district heating demand backed up by a solar thermal collector array;

Approach

• Screening and material characterization of candidate PCMs:
  • 30 – 60 °C – Space heating;
  • 70 – 90 °C – District heating;
  • 120 – 250 °C – medium temperature thermal applications;

• Numerical model verification with experimental work;

• Optimize prospective storage containers for the required heating source;
  • Space heating;
    • Backed up by a heat pump;
  • District heating
    • Constant heat supply (industrial waste heat);
    • Varying heat supply (solar thermal);
Progress

- Publication of “TES for low and medium temperature applications using PCMs- A Review” into Applied energy;

- Paper submission of the thermal analysis made to PCM candidates between 0 and 250 °C into The Journal of Chemical Thermodynamics;

- Presentation at the HTFF (Heat transfer and fluid flow) conference held in Hungary August 2016;
Packed bed model developed

- Packed bed thermal energy storage with macro-encapsulated PCM spheres;
- Charged and discharged with a flow rate, transferring convective heat to the PCM’s outer capsules;
  - Heat transfer flow equations based on known packed bed correlations retrieved from [1];
- No volume changes during phase change;
- Isotropic heat propagation among the PCM;
- Constant PCM’s thermal conductivity;
- Temperature-driven heat capacity curves accounted phase change;

Packed bed model in longitudinal cross section (A), transversal cross section with possible spheres arrangement (B) and detailed view of the division process within the sphere (C).

Packed bed model verification

- Tanvir et al [2], tested 770 spheres containing sodium nitrate between 286 and 326 °C;
- Air was used as the heat transfer fluid, in figure 3 is presented a schematic diagram, the experiment properties are resumed in table 2;
- Packed bed model followed the inlet-outlet experimental temperatures with good accuracy, with slight differences in the melting process due to not accounting the molten PCM buoyancy effects;

Table 2: Properties of the experimental work performed by Tanvir et al. [2]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed height [mm]</td>
<td>254</td>
</tr>
<tr>
<td>Bed Diameter [mm]</td>
<td>254</td>
</tr>
<tr>
<td>Total Volume of packed bed [L]</td>
<td>12.87</td>
</tr>
<tr>
<td>Bed Porosity</td>
<td>0.35</td>
</tr>
<tr>
<td>HTF:</td>
<td></td>
</tr>
<tr>
<td>Flow rate [m³/s]</td>
<td>0.0419</td>
</tr>
<tr>
<td>Reynolds Number (Re)</td>
<td>1293 - 1171</td>
</tr>
<tr>
<td>Prandtl (Number)</td>
<td>0.77</td>
</tr>
<tr>
<td>Nusselt Number (Nu)</td>
<td>52.3 – 49.6</td>
</tr>
<tr>
<td>Convection HT coefficient (h_cv) [W/m².K]</td>
<td>86 - 87</td>
</tr>
</tbody>
</table>

Domestic space heating network

- Backed up by a heat pump, and integrated into the domestic space heating network according diagram presented;
- Heat to the radiators supplied by the LHES container, with the heat pump working only during off peak times in economy 10 mode;

Integration of a LHS container into a conventional domestic central heating network
Domestic space heating network

- The objective was to retrofit the gas boiler by a heat pump, reduce CO₂ emissions operating in off peak times;

UK’s national grid demand on the 15th January 2015, and the correspondent CO₂ emissions
Calorimetric analysis

DSC results of their eutectic mixture

- Lower heat rates give more accurate results of the material’s thermal response;
- Heat rates lower than 1 K/min are very sensitive to noise;
Materials screening and characterization

- Salt hydrates eutectic mixture presented the most interesting properties;
- High storage density;
- Relatively good thermal conductivity;
- The system would need to operate up to 65°C to fully melt the PCM;

<table>
<thead>
<tr>
<th>PCM Candidates</th>
<th>( T_{\text{melt}} )</th>
<th>( H_{\text{melt}} )</th>
<th>( \lambda )</th>
<th>( \rho_s )</th>
<th>( E_{\text{density}} ) (from 40 to 65°C)</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C</td>
<td>kJ/kg</td>
<td>w/m.K</td>
<td>kg/m³</td>
<td>kWh/m³</td>
<td>£/m³</td>
</tr>
<tr>
<td>Paraffin Wax (RT54HC)</td>
<td>53</td>
<td>150</td>
<td>0.200</td>
<td>880</td>
<td>55</td>
<td>421</td>
</tr>
<tr>
<td>SA - PA</td>
<td>54</td>
<td>178</td>
<td>0.260</td>
<td>971</td>
<td>61</td>
<td>351</td>
</tr>
<tr>
<td>SP55 (SH-SH)</td>
<td>58</td>
<td>150</td>
<td>0.610</td>
<td>1610</td>
<td>83</td>
<td>92</td>
</tr>
</tbody>
</table>

Overlay of the heat capacity curves of the 3 candidate PCMs
The UK’s Detached and semi-detached dwellings represent the vast majority (around 70% according to Summerfield et al. [3]) of the British household market;

The study considered improved dwellings (better insolation, air tight, etc.)

Table 4 - Household properties, obtained from Mckenna et al model [4]

<table>
<thead>
<tr>
<th>Dwelling</th>
<th>Detached</th>
<th>Semi-detached</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>30.02</td>
<td>20.14</td>
<td>kWh</td>
</tr>
<tr>
<td>E LHS</td>
<td>10.01</td>
<td>7.15</td>
<td>W/K</td>
</tr>
<tr>
<td>UA</td>
<td>70.45</td>
<td>51.62</td>
<td>W/m².K</td>
</tr>
<tr>
<td></td>
<td>0.518</td>
<td>0.593</td>
<td>W/m².K</td>
</tr>
<tr>
<td>Floor area</td>
<td>136</td>
<td>87</td>
<td>m²</td>
</tr>
<tr>
<td>Inside volume</td>
<td>332</td>
<td>239</td>
<td>m³</td>
</tr>
<tr>
<td>Set temp.</td>
<td></td>
<td>19</td>
<td>°C</td>
</tr>
</tbody>
</table>

Daily heat demand

- Demand data generated by CREST high-resolution stochastic integrated domestic demand model developed by McKenna and Thomson [4];

- The latent heat system supplied 8h of space heating:
  - During 05.00 to 13.00;
  - During 16.00 to 24.00;

Modelling results

- Isothermal stage in the PCM during phase change proved useful to endure 8h of space heating;
- The packed bed was successful in offsetting the heat pump operating times;
- CO2 emissions reduction was 30% in the detached and 17% in the semi-detached dwelling;
- Reductions will come more promising if increased efforts in decarbonizing the grid are in place;

Results obtained in the Matlab analysis for the detached and semi-detached dwellings.
Future work

• Integrate a packed bed into a centralized commercial ventilated space heating and cooling network according to diagram presented;

• The heat being supplied by:
  • Air source heat pumps;
  • Solar thermal;
  • Night air cooling;

Integration of a LHS container into a centralized ventilated heating and cooling network
Thank You for the attention

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