Innovation in carbon-ammonia adsorption heat pump technology: a case study

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Introduction

The Carbon Plan and the Strategic Framework stated that meeting the 80% CO₂ reduction targets will need emissions from buildings to fall near zero by 2050.

This will need promoting a more efficient use of gas heating in the short to medium term, with gas use reduced to close to zero by 2050.

One way of helping to reduce the emissions of CO₂ is to develop a more efficient heat pump or refrigeration technology for domestic use.

The aim of this project was to develop a commercially viable heat driven carbon-ammonia heat pump system with a high efficiency (heating COP) and specific heating power (output power per kilo of adsorbent) using a shell and tube heat exchanger, an appropriate choice of adsorbent material and a four-bed cycle.
Introduction

The objectives of the project were:

- To carry out the computational modelling of a four-bed heat pump cycle.

- To carry out a heat transfer study of the active carbon available for the heat pump in order to identify the best sorbent sample.

- To design, manufacture and test the modelled heat pump cycle in order to validate the computational modelling.
Background
**Adsorption cycle operation**

Stage (a): system is at low pressure and ambient temperature. Adsorbent contains high concentration of adsorbed refrigerant whilst the right hand vessel contains refrigerant gas.
- Left vessel is heated. Adsorbed refrigerant gets driven out and the pressure of the system increases.

Stage (b): pressure of the system high enough so that the refrigerant gas condenses in the right vessel rejecting heat.
- Left generator cooled back to initial low temperature readsoorbing the refrigerant in the adsorbent material. Pressure of the system drops, the liquid refrigerant boils and produces the cooling effect, absorbing heat.

Stage (c): system back to initial state, cycle completed.

**Discontinuous heating/cooling**
Adsorption cycle - described in four stages:

Stage 1 $\rightarrow$ 2 – Isosteric pressurisation

Stage 2 $\rightarrow$ 3 – Isobaric desorption

Stage 3 $\rightarrow$ 4 – Isosteric depressurisation

Stage 4 $\rightarrow$ 1 – Isobaric adsorption
Continuous basic cycle - COP

COP of the basic cycle → LOW

Heat regeneration techniques:
• Multiple bed cycles heat recovery between the generators

\[
COP_{heating} = \frac{Q_{\text{cond}} + Q_{\text{cooler}}}{Q_{\text{boiler}}}
\]

\[
COP_{cooling} = \frac{Q_{ev}}{Q_{boiler}}
\]
Specifications of the product and system design
Domestic heat pump – UK market

- Box-for-box exchange for conventional gas boiler → Retrofit market (90% of annual sales)

- 7kW (3 bedroom semi-detached house at 18 °C)
- 30 - 40% reduction in gas consumption
- Air source
System design

- Bed 4
- Bed 3
- Gas Burner
- Hot Gases
- Warm Exhaust Gases
- Air-to-Pressurised Water Heat Exchanger
- Inlet Air
- Final Exhaust Heat Exchanger
- Cool Exhaust Gases
- Adsorbent Bed 1
  - Heated
- Adsorbent Bed 2
  - Cooled
- Adsorbent Bed 3
- Condenser
- Evaporator
- Ammonia
- Ambient Air to Evaporator
- Cooled Air from Evaporator
- Return water from house
- Heated water to house
Generator design
Generator core

Condenser / evaporator
Relief valve
Pressure transducer

o-ring grooves

Generator shell

400 mm
150 mm
Nickel brazing 1777 tubes

Rapid prototype spiral distributor

Front

Back
Sorption material specifications and thermal properties enhancement
# Carbon grains and powder

100% grains – X% grains + X% powder – 100% powder

<table>
<thead>
<tr>
<th>Size</th>
<th>Max. sieve opening (μm)</th>
<th>Min. sieve opening (μm)</th>
<th>Bulk density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 x 30 USS</td>
<td>1700 μm</td>
<td>600 μm</td>
<td>560 kg/m³</td>
</tr>
<tr>
<td>20 x 40 USS</td>
<td>850 μm</td>
<td>425 μm</td>
<td>527 kg/m³</td>
</tr>
<tr>
<td>30 x 70 USS</td>
<td>600 μm</td>
<td>212 μm</td>
<td>553 kg/m³</td>
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<tr>
<td>50 x 100 USS</td>
<td>300 μm</td>
<td>150 μm</td>
<td>513 kg/m³</td>
</tr>
<tr>
<td>Powder</td>
<td>180 μm</td>
<td>0 μm</td>
<td>544 kg/m³</td>
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</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Carbon type</td>
<td>Chemviron 208C</td>
</tr>
<tr>
<td>Solid carbon thermal conductivity</td>
<td>0.85 W/(mK)</td>
</tr>
<tr>
<td>Limiting concentration</td>
<td>0.2551 kg/kg</td>
</tr>
</tbody>
</table>

[Image of carbon grains and powder]
Carbon thermal properties measurements

1. Steady state flat plates

2. Transient hot tube
Steady state flat plates measurements

- 2-inch diameter plates
- Calibration lines for round and square samples needed

Thermal conductivity in parallel and perpendicular direction of compression
Transient hot tube measurements

4 wire technique

Simulation program needed for analysis
Results: thermal conductivity
Results: wall contact resistance

Contact air layer thickness (mm) vs. Density (kg/m³)

- 100% grains
- Mixtures
- 100% powder
Thermal properties vs generator geometry

For a generator U-value of 600 W/(m²K)
# Carbon choice and filling process

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture type</td>
<td>⅔ 20x40 grains &amp; ⅓ powder</td>
</tr>
<tr>
<td>Carbon mass</td>
<td>3 kg</td>
</tr>
<tr>
<td>Sorption material volume</td>
<td>4.7 l</td>
</tr>
<tr>
<td>Packed density</td>
<td>640 kg/m³</td>
</tr>
<tr>
<td>Packed thermal conductivity</td>
<td>0.3 W/(mK)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pore size / Aperture size</th>
<th>Thickness / Wire diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass filter</td>
<td>1.2 µm</td>
</tr>
<tr>
<td>Fine gauze</td>
<td>0.026 mm</td>
</tr>
<tr>
<td>Coarse gauze</td>
<td>0.049 mm</td>
</tr>
</tbody>
</table>
Model programming
• Generator
Two-dimensional finite difference grid

- Condenser
- Evaporator
- Cooler
- Receiver
- Check valve

Matlab®
Simulation results
Carbon temperature over a cycle (one bed)

- \( t = 260 \text{ s} \)
- \( mw = 0.0375 \text{ kg/s} \)
- \( K_C = 0.3 \text{ W/(mK)} \)
- \( T_{\text{HOT}} = 170 \degree \text{C} \)
- \( T_{\text{cond}} = 40 \degree \text{C} \)
- \( T_{\text{ev}} = 0 \degree \text{C} \)
Ammonia pressures over a cycle

$t = 260 \text{ s}$  $mw = 0.0375 \text{ kg/s}$  $K_C = 0.3 \text{ W/(mK)}$

$T_{HOT} = 170 \degree \text{C}$  $T_{\text{cond}} = 40 \degree \text{C}$  $T_{\text{ev}} = 0 \degree \text{C}$
Adsorbed ammonia over one cycle (one bed)

\[ t = 260 \text{ s} \quad mw = 0.0375 \text{ kg/s} \quad K_C = 0.3 \text{ W/(mK)} \]

\[ T_{\text{HOT}} = 170 \degree \text{C} \quad T_{\text{cond}} = 40 \degree \text{C} \quad T_{\text{ev}} = 0 \degree \text{C} \]
Performance envelope

<table>
<thead>
<tr>
<th>T_{HOT} = 170 °C</th>
<th>T_{cond} = 40 °C</th>
<th>T_{ev} = 0 °C</th>
<th>K_c = 0.3 W/(mK)</th>
</tr>
</thead>
</table>

- mw = 0.025 kg/s
- mw = 0.03 kg/s
- mw = 0.0375 kg/s
- mw = 0.045 kg/s
- mw = 0.06 kg/s
- mw = 0.075 kg/s
- mw = 0.1 kg/s

Envelope
Performance map

\[ T_{\text{HOT}} = 170 \, ^{\circ}\text{C} \quad T_{\text{cond}} = 40 \, ^{\circ}\text{C} \quad T_{\text{ev}} = 0 \, ^{\circ}\text{C} \quad K_C = 0.3 \, \text{W/(mK)} \]

- COPh mw = 0.025 kg/s
- COPh mw = 0.03 kg/s
- COPh mw = 0.0375 kg/s
- COPh mw = 0.045 kg/s
- COPh mw = 0.06 kg/s
- COPh mw = 0.075 kg/s
- COPh mw = 0.1 kg/s
- SHP mw = 0.025 kg/s
- SHP mw = 0.03 kg/s
- SHP mw = 0.0375 kg/s
- SHP mw = 0.045 kg/s
- SHP mw = 0.06 kg/s
- SHP mw = 0.075 kg/s
- SHP mw = 0.1 kg/s
Effect of driving temperature on COPh and SHP

\[ T_{\text{cond}} = 40 \, ^\circ\text{C} \quad T_{\text{ev}} = 0 \, ^\circ\text{C} \quad K_C = 0.3 \, \text{W/(mK)} \]

![Graph showing the effect of driving temperature on COPh and SHP](image)
Effect of condensing and evaporating temperatures on COPh and SHP

$T_{\text{HOT}} = 170 \, ^\circ\text{C}$

$K_C = 0.3 \, \text{W/(mK)}$

---

Effect of condensing and evaporating temperatures on COPh and SHP

$T_{\text{HOT}} = 170 \, ^\circ\text{C}$

$K_C = 0.3 \, \text{W/(mK)}$

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Effect of condensing and evaporating temperatures on COPh and SHP

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Effect of condensing and evaporating temperatures on COPh and SHP

$T_{\text{HOT}} = 170 \, ^\circ\text{C}$

$K_C = 0.3 \, \text{W/(mK)}$

---
Relationship between COPh and output water temperature for a 7 kW machine and different evaporating temperatures (comparison with a condensing boiler efficiency)

\[ T_{\text{HOT}} = 170 \, ^{\circ}\text{C} \]
Effect of adsorbent thermal conductivity

![Graph showing COPh vs SHP (kW/kg) with lines and markers for 0.1 W/(mK) and 0.3 W/(mK) and envelopes for 0.1 W/(mK) and 0.3 W/(mK).]
Comparison of modified cycle simulations

Water temperature (°C)

Time (s)

- Ideal In
- Ideal Out
- Delays In
- Delays Out
- Delays Speed Pump In
- Delays Speed Pump Out
- Smooth delays Speed Pump In
- Smooth delays Speed Pump Out
- With convection effect In
- With convection effect Out
Comparison of modified cycle simulations

- Ideal
- Delays Speed Pump
- With convection effect
- Delays
- Smooth delays Speed Pump
Comparison of modified cycle simulations

<table>
<thead>
<tr>
<th>Type of cycle</th>
<th>COPh</th>
<th>Power output (kW)</th>
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<tbody>
<tr>
<td>Ideal</td>
<td>1.49</td>
<td>6.77</td>
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<tr>
<td>Delays</td>
<td>1.43</td>
<td>6.65</td>
</tr>
<tr>
<td>Delays and speed pump effect</td>
<td>1.38</td>
<td>6.47</td>
</tr>
<tr>
<td>Smooth delays and speed pump effect</td>
<td>1.35</td>
<td>6.23</td>
</tr>
<tr>
<td>Smooth delays, speed pump and convective effect</td>
<td>1.33</td>
<td>6.33</td>
</tr>
</tbody>
</table>
Comparison of modified cycle simulations

Water mass flow rate = 0.025 kg/s

Water mass flow rate = 0.1 kg/s
Construction of prototype system, instrumentation and control
Ammonia pipework system
Complete built system

Gas burner?
Complete built system

Water valves
Check valves
Pressure transmitters
Load pump
Water valve actuators
Bed pump
Check valves

Poppet type

Ball type
Check valve challenge: salts formation
Check valves → Pneumatic valves

• If $p_{\text{bed}} > p_{\text{cond}}$ or $p_{\text{bed}} < p_{\text{ev}}$
  - Bed opened for 6 s
• Bed closed for 2 s
• Re-evaluation of pressures
Water valves

4 - poles
4 - way switches

PEEK and brown alumina
Experimental results and analysis, steady state performance tests
Insulation and heat loss test

- \( T_{\text{chamber}} = 10 \, ^\circ\text{C} \)
- \( T_{\text{w,inlet}} = 95 \, ^\circ\text{C} \)

Heat loss = 520 W
Experimental results

- $T_{\text{HOT}} = 123 \, ^\circ\text{C}$
- $T_{\text{cond}} = 30 \, ^\circ\text{C}$
- $T_{\text{ev}} = 11.5 \, ^\circ\text{C}$
- $m_w = 0.032 \, \text{kg/s}$
- $t = 400 \, \text{s}$

- COPh = 1.18 (1.31) - SHP = 4.51 kW (4.30 kW)
- COPh = 1.67 - SHP = 4.84 kW
Modelling simulation comparison

\[
\text{COPh} = 1.18 \ (1.31) \quad \text{SHP} = 4.51 \ , \ 4.30 \ kW
\]

\[
\text{COPh} = 1.67 \quad \text{SHP} = 4.84 \ kW
\]
Experimental results

<table>
<thead>
<tr>
<th>Temperature (C)</th>
<th>Time (s)</th>
<th>Bed A In</th>
<th>Bed A Out</th>
<th>Bed B In</th>
<th>Bed B Out</th>
<th>Bed C In</th>
<th>Bed C Out</th>
<th>Bed D In</th>
<th>Bed D Out</th>
<th>Hot Return</th>
<th>Hot Flow</th>
<th>Cooler Out</th>
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<tbody>
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<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Time (s)</th>
<th>Bed A</th>
<th>Bed B</th>
<th>Bed C</th>
<th>Bed D</th>
<th>Condenser</th>
<th>Evaporator</th>
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<td>488</td>
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</tr>
</tbody>
</table>

| T_HOT = 148 °C  | m_w = 0.032 kg/s |
| TCond = 42 °C   | t = 480 s       |
| T_eV = 10 °C    |                 |

\[ \text{COP}_h = 1.13 \text{ (1.26)} - \text{SHP} = 4.92 \text{ kW (5.19 kW)} \]

\[ \text{COP}_h = 1.48 - \text{SHP} = 5.73 \text{ kW} \]
Modelling simulation comparison

**Temperature (°C)**
- Bed A in - Simulation
- Bed A in - Experiment
- Bed A out - Simulation
- Bed A out - Experiment
- Hot flow - Simulation
- Hot flow - Experiment
- Hot return - Simulation
- Hot return - Experiment
- Cooler out - Simulation

**Pressure (bar)**
- Bed A - Simulation
- Bed A - Experiment
- Condenser - Simulation
- Condenser - Experiment
- Evaporator - Simulation
- Evaporator - Experiment

**COPh = 1.13 (1.26) - SHP = 4.92 kW (5.19 kW)**

**COPh = 1.48 - SHP = 5.73 kW**
Challenges encountered

Blocked generator tubes
Conclusions
All the project objectives initially presented were met:

- The design and manufacturing process of a low thermal mass and high density power sorption shell and tube heat exchanger was carried out.

- The performance of the four-bed heat pump cycle was analysed through computational modelling and compared with experiments for many different set of conditions in order to understand its behaviour and the effect these conditions have on the heating COP and heat output power.

- Measurements of the heat transfer properties of the active carbon were carried out. The thermal conductivity and wall contact resistance of carbon samples was tested by steady state flat plate and transient hot tube technique.
• Binary mixtures of grains and powder were tested and it was found that they could achieve much higher densities, higher thermal conductivities and lower contact resistances at the same vibration or compression rates than grains on their own.

• The laboratory heat pump system was designed and constructed to test the adsorption generators and cycle. The testing of the machine showed results that were lower than the simulation predictions.

• After the testing, the beds were opened and it was discovered that the installed water distributors were completely distorted and deformed, blocking most of the tubes of the heat exchanger. This was the main reason for the low performance of the machine.
Future work
Future work

• The generators manufacturing technique should be developed in order to being able to mass produce them at a low cost. Improve marketability.

• The generators spiral water distributors should be remanufactured in a material that does not deteriorate at the heat pump driving water temperature (around 170 °C). A proposed material to use would be aluminium due to its high thermal conductivity, high fusion temperature and easy machinability.
Future work

• Better positioning of the water valves and generators in order to reduce dead volumes of water that affect the system efficiency.

• Development of a carbon pre-treatment to remove the impurities that react with ammonia creating the ammonia salts presented that were cause of pipe blockages and check valves jamming.

• More research on heat transfer in carbon beds such as wall contact resistance reduction and thermal conductivity of carbon increase. This would lead to a reduction of the adsorption generators size and would make the system more compact and marketable.
Thank you for your attention!

Questions and Answers time
We hope you enjoyed this webinar from the Institute of Refrigeration

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