Heating and Cooling to 2020 and Beyond

Prof Bob Critoph
University of Warwick

Sustainable Thermal Energy Management International Conference (SusTEM2015), July 7th – 8th, United Kingdom
The UK is committed to a reduction in greenhouse gas emissions of 80% by 2050 across all sectors.
Context

- In 2011, RCUK initiated a call to fund up to six interdisciplinary Centres in ‘End Use Energy Demand’. Each Centre would be funded for five years initially with a nominal budget of £5M.
- i-STUTE was awarded one of the centres and funding commenced from April 2013 – its distinctive feature is concentration on heating and cooling.
Societal needs and practices

Energy security
Fuel poverty

Individual needs
Functions:
• Comfort
• Health
• Hygiene
• ...

Energy Trilema

Supply technology
Demand technology
DSM

Energy efficiency

Emissions
Interdisciplinary centre for Storage, Transformation and Upgrading of Thermal Energy
Why heating and cooling?

- 47% of fossil fuels in the UK are burnt for low temperature heating purposes (25% of CO$_2$ emissions)
- 16% of electricity in the UK used to provide cooling - Worldwide it represents 10% of greenhouse gas emissions

Energy Consumption by end use 2012

- Heat 47%
- Transport 39%
- Other 14%

Provisional data for 2012 (DECC)
Energy Consumption by end use 2012

- Heat: 47%
- Transport: 39%
- Other: 14%

Heat Use by Sector

- Domestic: 57%
- Industry: 24%
- Service: 19%

Provisional data for 2012 (DECC)
Heat use by purpose

- Space heating: 63%
- Water heating: 14%
- Cooking/catering: 5%
- High temperature process: 6%
- Drying/separation: 3%
- Low temperature process: 9%

Breakdown by fuel of total heat use

- Gas: 71%
- Electricity: 15%
- Oil: 7%
- Solid fuel: 3%
- Bioenergy & Waste: 2%
- Heat sold: 2%

i-STUTE coverage in red
i-STUTE Rationale

• Even after:
  o Use of optimised industrial processes
  o Improved insulation and reduced infiltration in buildings
  o User behavioural change,

  a large increase in the energy efficiency of heating and cooling through technology will be needed if the 2050 target is to be met.

• Direct combustion of fuels for heat production at temperatures up to 200°C is inherently wasteful since a range of heat pumping and storage technologies could be used to meet this heat demand with dramatically reduced CO₂ emissions.
Who are we, what do we do?

WARWICK
THE UNIVERSITY OF WARWICK
• Thermal heat pumps
• Business models

Loughborough University
• Thermal energy storage
• Consumer behaviour

London South Bank University
• Commercial and industrial refrigeration
• Engagement with SMEs

Ulster University
• Electric heat pumps
• Integration with storage
Who are we, what do we do?

Bob Critoph
David Elmes
Victoria Haines
Graeme Maidment
Judith Evans
Phil Eames
Neil Hewitt
Why interdisciplinary?

• Solutions must be:
  – Technically feasible
  – Consumer friendly
  – Politically acceptable
  – Economically viable
  – Have a business model and route market that ensures development

• How will we integrate these?
New technologies, business models and behaviours

Advisory Board
- Government
- Utilities
- Industry
- Consumer interests

Underpinning Science and Technology
Heat pumps (domestic/industrial)
Commercial refrigeration, Heat storage

Economic, social and policy enablers, constraints
- Consumer behaviour
- Business models
- Policy and regulation
- Supply chain and manufacture
- Integration with future infrastructure

INTEGRATION
Underpinning Science and Technology

INTEGRATION

Advisory Board
- Government
- Utilities
- Industry
- Consumer interests

Economic, social and policy enablers, constraints
- Consumer behaviour
- Business models
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- Integration with future infrastructure

Underpinning Science and Technology
- Heat pumps (domestic/industrial)
- Commercial refrigeration, Heat storage

New technologies, business models and behaviours
- Heat pumps
- Commercial refrigeration
- Heat storage

Industrial dissemination
Academic dissemination
Policy briefings
Capability development
Roadmaps
Advisory Board – Industry and International members
Work packages in:

• Cooling / refrigeration
• Low temperature heating
• Industrial heat
• Business models
• Consumer behaviour / acceptability
+
• Dissemination

i-STUTE – www.i-STUTE.org
SIRACH - (Sustainable Innovation in Refrigeration, Air Conditioning and Heat Pumps) www.sirach.org.uk
• A dissemination network
• Sustainable Innovation in Refrigeration, Air Conditioning and Heating
• Built on SIRAC – a successful Network with 400 members, website, etc
<table>
<thead>
<tr>
<th>Event name</th>
<th>Date</th>
<th>Subject</th>
<th>Attendees</th>
</tr>
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<tr>
<td>Emerson Technologies, Northern Ireland</td>
<td>25 February 2014</td>
<td>Heat pump and compressors</td>
<td>29</td>
</tr>
<tr>
<td>Spirax Sarco, Cheltenham</td>
<td>21 May 2014</td>
<td>Heat powered cycles</td>
<td>36</td>
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<tr>
<td>ICCC International Conference - London</td>
<td>25 June 2014</td>
<td>Challenges to implementing sustainability</td>
<td>35</td>
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<td>Mitsubishi Electric – Edinburgh</td>
<td>2 September 2014</td>
<td>Innovation in Air Conditioning and Heat Pumps</td>
<td>32</td>
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<tr>
<td>Sainsbury’s Supermarket – Leicestershire</td>
<td>22 October 2014</td>
<td>Commercial refrigeration, cooling and heating</td>
<td>50</td>
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<tr>
<td>Climate Center – Leamington Spa</td>
<td>5 February 2015</td>
<td>Components for Air Conditioning and Heat Pumps</td>
<td>42</td>
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<tr>
<td>Arctic Circle, Hereford</td>
<td>23 April 2015</td>
<td>Development in Heating and Cooling Technologies</td>
<td>35</td>
</tr>
<tr>
<td>IRC Congress, Yokohama, Japan</td>
<td>16 - 22 August 2015</td>
<td>Sustainable heating and cooling</td>
<td></td>
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<tr>
<td>Newcastle University</td>
<td>September 2015</td>
<td>Energy Storage</td>
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<td>Birmingham University</td>
<td>November 2015</td>
<td>A commission on cold</td>
<td></td>
</tr>
</tbody>
</table>
Innovation in Air Conditioning and Heat Pumps (Edinburgh)  November 2014

Commercial refrigeration, cooling and heating (Leicester)  January 2015

Components for Air Conditioning and Heat Pumps (Leamington Spa)  March 2015

An eye on the future of heating and cooling technologies - Introduction  April 2015

**Upcoming Articles**

Magnetic heating and cooling  Due May 2015

Development in Heating and Cooling Technologies (Hereford)  Due June 2015

Thermoacoustic  Due July 2015

Absorption  Due August 2015

Sterling cycle  Due September 2015

Thermoelectric  Due October 2015

District Heating and Cooling (Newcastle University)  Due November 2015

Adsorption  Due December 2015
## Current Projects

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<tr>
<th>Next generation gas/heat powered heat pump</th>
<th>Thermal transformers</th>
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<td>Advanced electric heat pump</td>
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<td>Compact chemical/latent heat store</td>
<td>Retail chilling and freezing</td>
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<td>Behaviour and Business Models: adoption and commercialisation</td>
<td>Data centres</td>
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</table>
Current Projects

Next generation gas/heat powered heat pump
Compact chemical/latent heat store
Advanced electric heat pump

Behaviour and Business Models:
adoption and commercialisation
Low temperature heat emitters
Retail chilling and freezing
Data centres
Thermal transformers

• Not a full list
• Not everything that is important
• A combination of what is within our expertise and what promises major CO$_2$ emission reductions
i-STUTE cooling based projects

Supermarket refrigeration

Data centres

Transport refrigeration

Integrated heating and cooling

Cost of ownership

Carbon/energy

Integration

Materials, resources & waste
Retail chilling and freezing

Background

• 40-70% of energy in supermarkets used for refrigeration
• UK retail refrigeration ~ 9-10 TWh/year
  — ~75% chilled, ~25% frozen
• 1.5% of UK energy used by retail
• ~7.3 Mt CO2 (~26% direct, ~74% indirect)
• Temperature control, carbon emissions increase at consumer end of cold chain

Deliverables

• Refrigeration road map
• State of the art display cabinet
The model

- Supermarket model further developed
- Store modelled - ASDA Weston-Super-Mare
- Typical large supermarket
- Model can be adapted to different store sizes and configurations
Results

- Emissions per year:
  - Direct = 343.8 t\(\text{CO}_2\text{e}\)
  - Indirect = 373.7 t\(\text{CO}_2\text{e}\)
- Ratio indirect : direct = 1.1
- High direct as very high refrigerant charge (~1000 kg in cabinet circuits)
- Leakage rate medium (~10% per year)
- Therefore effect of changes to refrigerant have high impact on \(\text{CO}_2\text{e}\) emissions
Technologies investigated

- 77 technologies evaluated
- New technologies added:
  - Ejectors
  - Flooded evaporators
  - 2-stage compression
  - Turbine expansion machines
  - Fan motor outside cabinet
  - Lights outside cabinet
  - Defrost drain traps
  - Integral distributed system
  - Thermostatic flow control
  - Air deflectors/guides
  - Improved axial fans
  - Diagonal fans
  - Defrosts (additional information)
  - Dual port TEV/TXV
  - Glazing (additional information)
  - Efficient HE design
  - Hydrophilic and hydrophobic coating on evaporator
Results

- Based on current information possible to halve emissions with paybacks of less than 3 years
- If technologies with less than 3 year paybacks were applied and assuming application of:
  - Cheapest options with best paybacks
  - Minimum savings applied
  - Simplest option (where more than one option available)
- the carbon savings would be:
  \(~50 - 65\%~\)
i-STUTE cooling based projects

Supermarket refrigeration

Data centres

Transport refrigeration

Integrated heating and cooling

Cost of ownership

Carbon/energy

Integration

Materials, resources & waste
Data Centre Cooling

Background
• Data centres currently account for approx. 2-3% of total electricity consumption in the UK

• Typically, approx. 50% of data centre energy is used for cooling and humidification

• Data centres are generally air cooled and the heat dissipated to ambient

• Limited focus on heat recovery

Deliverables
• Roadmap/report on cooling

• Detailed investigation - integrated cooling, heat recovery and heat transfer.
Roadmap

There are 4 main approaches to data centre cooling:

Remote air cooling:
- Using CRACs or CRAHs/chilled water. Also air and water economisation

Local air cooling:
- Close coupled cooling e.g. rack rear door chilled water heat exchanger

Direct liquid on-chip cooling:
- Water or dielectric cold plate heat exchanger in direct contact with electronic components

Total immersion liquid cooling:
- Whole server board immersed in dielectric liquid
Detailed investigation of cooling and waste heat recovery in data centres

Objectives:

To construct a test facility to simulate a conventional IT server rack (~5kW)

To investigate a range of cooling methods, environmental conditions and waste heat recovery systems

- To evaluate the quantity and quality of recovered waste heat, for different cooling methods

- To investigate the carbon and cost implications of increasing waste heat temperature to e.g. 70°C using heat pumps
Data centres and District heating networks

・ Currently supply only 2% of heat demand in UK by district heating

・ UK government plans to substantially expand district heating networks making use of waste heat sources e.g. data centres

・ London plans to build a low temperature heat network – supply temperature 70°C (London Mayor reports, 2012; 2013)

・ Data centre waste heat could be upgraded via heat pumps to contribute heat at this temperature
i-STUTE cooling based projects

Supermarket refrigeration

Data centres

Transport refrigeration

Integrated heating and cooling

Cost of ownership

Integration

Carbon/energy

Materials, resources & waste
Refrigerated road transport (RRT)

Background
• UK primary food distribution by RRT uses 40% more energy than non-refrigerated vehicles
• Environmental Impact
  • Indirect emissions -
    • Transportation - 2 Mtonnes of indirect CO₂ emissions from the engine alone.
    • Refrigeration - ???
  • Direct emissions -
    • RRT units leak up to 30% of their total refrigerant charge per year
    • System Durability & Reliability

Deliverables
• Development of a model to investigate direct and indirect emissions
• Optimising system performance
### Projects in Space Heating

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<tbody>
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<td>Next generation gas powered heat pump</td>
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<td>Heat emitter study</td>
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</table>
Compact chemical/latent heat store

Domestic Heat pumps cannot economically provide the high powers (25kW) required for instantaneous hot water production

Grid limitations prevent instantaneous demand heat pumps. 4 – 7 x Electricity distribution network capacity needed? Rewire +250,000 km in 15-30 years?

Compact chemical/latent heat store

**Rationale:**

- Hybrid electric heat pump/gas boilers have been suggested as one solution but as the housing stock thermal performance improves, DHW provision will become a larger fraction of the total load.

Source: E. Sutherland, Bosch, Bosch Hybrid, GasTech seminar 19th March 2012
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- Hybrid electric heat pump/gas boilers have been suggested as one solution but as the housing stock thermal performance improves, DHW provision will become a larger fraction of the total load.

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Compact chemical/latent heat store

**Rationale:**

- Hybrid electric heat pump/gas boilers have been suggested as one solution but as the housing stock thermal performance improves, DHW provision will become a larger fraction of the total load.

- Another option is the gas fired heat pump – three products on or near market:
Compact chemical/latent heat store

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- Hybrid electric heat pump/gas boilers have been suggested as one solution but as the housing stock thermal performance improves, DHW provision will become a larger fraction of the total load.

- Another option is the gas fired heat pump – three products on or near market:

  **Technical data of Vaillant zeoTHERM VAS 106/4**
  
  - Rated heat output range Heating: 1.5-10 kW
  - Rated heat output range d.h.w.: 4.2-12.5 kW
  - Adjustable flow temperature: 20-75 °C
  - Recommended max. flow temperature HC < 40 °C
  - El. power consumption max.: 100 W
  - Appliance width: 772 mm
  - Appliance height incl. flue outlet: 1.700 mm
  - Appliance depth: 718 mm
  - Transport weight (without casing): 160 kg
  - Operating weight: 175 kg
Compact chemical/latent heat store

**Rationale:**

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- Another option is the gas fired heat pump – three products on or near market:

**Viessmann Gas-Fired Zeolite Compact Heating Appliance**

Features at a glance

- Hybrid Heating Appliance:
  - Heating Power Modulation: 1.6 to 10 kW (1 to 7) Booster capacity for DHW: 15 kW
- SGUE Heating (VDI 4650-2): 135 % (Hi 35/28 °C)
  - SGUE Heating (VDI 4650-2): 125 % (Hi 55/45 °C)
- Ambient Heat Source: 2013 GHS
  - From 2014 also Solar
- Working pair completely environment friendly
- Installation, maintenance and service analog to condensing boiler compact units
- Gas-Fired Adsorption Heat Pump in the dimensions of Viessmann compact heating appliances
- Dimensions: BxHxT: 600x595x1875 mm
- Weight: <170 kg (separable in two parts)
Another approach to the problem is heat storage

Advanced compact heat stores can smooth out the diurnal peaks on the grid. They are part of a complex solution that involves hybrids, gas fired heat pumps and perhaps other technologies.

Latent heat energy storage (short term)

This project will develop and test a prototype system scalable to meet 2-4 hours of maximum winter space and water heating load.

Chemical heat store (long term)

Objective is to develop a chemical thermal energy store with an energy density of at least five times that of a comparable water store at 65°C.
Compact latent heat store

A range of organic and inorganic materials are being characterised to determine their latent heat and phase change temperature.

- Repeatability and Subcooling may be an issue for some materials tested.
- Corrosion tests are being performed for salts to determine material compatibility.
- A laboratory storage system of 1 kWh will be constructed when the most suitable material is selected and corrosion tests have been completed.
- Modelling of phase change for melting and solidification will be informed by materials characterisation.
Prediction of charging of a PCM store

Outlet Time = 2700 seconds

Outlet Time = 5400 seconds
## Projects in Space Heating

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</table>
Advanced electric heat pump

**Challenge:** To design robust and flexible control algorithms and reliable but efficient hardware based on improved cycles

**Objective:** Demonstrate an air to water heat pump in the field that is consumer friendly and delivers a seasonal COP > 3.0

**Rationale:** Present electric heat pumps perform well below laboratory levels in real applications and can be improved by cycle modifications and advanced control
Advanced electric heat pump (Ulster)

Previous Work:

Economised Vapour Injection
Advanced electric heat pump (Ulster)

Previous Work:

Field Trial

Average COP with ambient temperature

-5 0 5 10 15 20

Ambient Temperature (°C)

COP

63C 60C 58C 55C 50C

Linear (60C) Linear (58C) Linear (55C) Linear (50C)
Advanced electric heat pump (Ulster)

Stage 1: House Evaluation

Test house heating demand

Test house hot water demand
Advanced electric heat pump (Ulster)

Stage 2: Heat Pump Evaluation
Advanced electric heat pump (Ulster)

Stage 3: Heat Storage

Tank size capacity is 600 L with dimension 2000 x 600 mm. Tank has 75 mm of insulation compared to standard insulation (50 mm).

Data for both coils:
- Flow rate max: 30 l/min or 0.5l/s,
- Flow temperature: 70-75°C with ΔT=10K
- Tank volume: 600 litres approx.
Advanced electric heat pump (Ulster)

Stage 3: Heat Storage
Advanced electric heat pump (Ulster)

Stage 4: Integration
# Projects in Space Heating

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</table>
Next generation gas/heat powered heat pump

Rationale

- Up to 50% reduction in CO₂ emissions compared with domestic condensing boilers
- Inability of electricity supply system to cope with an ‘all electric’ future with all homes heated by electric heat pumps – gas (inc. biogas) still has a role to play

Technical options

- Engine driven heat pumps
  - Small sizes have maintenance and noise issues
- Sorption cycles [Absorption and Adsorption]
  - Very few moving parts
  - Potentially low cost
Gas-fired heat pumps

Previous Research at Warwick

Early concept ‘single box’, tested in environmental chamber 2011
Gas-fired heat pumps

Current research on i-STUTE

Present concept ‘split system’, evaporator outside house, other components within ‘look and feel’ like a gas boiler

- Box-for-box exchange for old boiler
- Fits into standard wall-mounted casing
- Designed for retrofit market
  >90% of annual sales
Original version, ‘Pre i-STUTE’
Tested May 2011

- Top valve assembly
- Generators
- Bottom valve assembly
- Gas heat exchanger
- Burner
- Evaporators
‘Pre i-STUTE’ Machine

• Machine suffered from excessive heat loss and high thermal mass in complex valve assemblies
• Machine produced hot water from gas, but at an efficiency little better than a gas boiler!
• Decision was made at the start of the i-STUTE project to simplify the system and make it less compactly packaged (for easier debugging)
• Switch from gas to electrical heat input to focus development on the heat pump itself
Efficiency increases with 4 beds and heat recovery

Gas Burner

Inlet Air

Return water from house

Cool Exhaust Gases

Warm Exhaust Gases

Air-to-Pressurised Water Heat Exchanger

Final Exhaust Heat Exchanger

Adsorbent Bed 1
Heated

Adsorbent Bed 2
Cooled

Condenser

Ammonia

Ambient Air to Evaporator

Evaporator

Cooled Air from Evaporator

Return water to house

Heated water to house
‘i-STUTE’ Simplified Lab System
Test Conditions

Driving Temperature: 150°C (Electrical Heat Input)

Evaporating temperature: 0-7°C

Delivery temperature:
- Underfloor heating: 36°C flow, 26°C return
- Low temp. radiators: 50°C flow, 40°C return
Test Results

COP (Heat Output to Heat Input)

Heating Power [kW]

Low Temp Rads
Underfloor Heating
Low Temp Rads Fit
Test Results

Example case for model comparison

COP (Heat Output to Heat Input)

Heating Power [kW]

- Low Temp Rads
- Underfloor Heating
- Low Temp Rads Fit
Generator Thermal Mass

- The generator is effectively a thermally driven compressor, and is the most critical part of the design
- The generator flanges contained 10 kg of stainless steel which reduced the COP
Generator Thermal Mass

- New domed end flange design reduces the mass of steel from 10kg to 2kg
- Currently undergoing manufacture
Model prediction for improved machine:

<table>
<thead>
<tr>
<th>Case</th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous design – 10 kg steel</td>
<td>1.29</td>
</tr>
<tr>
<td>New design – 2 kg steel</td>
<td>1.35</td>
</tr>
</tbody>
</table>
Predicted Performance

• For the example case of underfloor heating at 7 kW heat output, the overall COP (heat output to higher heating value of gas input) could then reach **1.2**

• An assessment of the performance with respect to the new Energy Related Products (ERP) labelling scheme is required to determine if our system would be rated A, A+ or A++
## Projects in Process Heating

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<tr>
<td>Process heat storage</td>
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<tr>
<td>Thermal transformers</td>
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</tbody>
</table>
High Temperature Electric Heat Pumps

Rationale:
• CO$_2$ emissions reduction from heat recovery in food and chemicals alone is $> 1.0$ MtCO$_2$ per year.
• Current heat pumps generally limited to 70-80°C output.
• Steam is the energy transfer medium of choice for industry and a steam raising heat pump solution is needed.
High Temperature Heat Pump

Applications

• Petroleum Industry
• Chemical
• Food & Beverages
• District Heating
• Nuclear Power
• Desalination
• Waste Water Treatment
HT Heat Pump
Theoretical Approach

- Alternative working fluid
- Multistage cycles
- Compressor performance
- Controlling system
- Materials, Oil, etc
Future Work
Challenges

• Alternative Working fluids (150°-200°C)
  • R245fa, R1234ze(Z), R365mfc
• Refrigerant Mixtures
• Compressor Technology
  • Lubricants
  • Sealing
• EXV Controllers
Experimental Work

STES District Heating - Poland

<table>
<thead>
<tr>
<th>Type of building</th>
<th>Hospital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar collectors</td>
<td>175 m²</td>
</tr>
<tr>
<td>STES Volume</td>
<td>800 m³</td>
</tr>
<tr>
<td>Demand temperatures</td>
<td>55/75°C</td>
</tr>
<tr>
<td>Solar Fraction</td>
<td>50%</td>
</tr>
<tr>
<td>Gas boiler (kW)</td>
<td>95 kW</td>
</tr>
</tbody>
</table>

Solar generation

Storage

Heat pump

Boiler

75°C

65°C
Experimental Work
R245fa Heat Pump

- Heating Capacity: 90kW
- Compressor: Stream semi-hermetic
- Compressor disp: 153 m³/h
- Single loop – Water to Water
- EXV: Electronic
- $T_{\text{evap}}$: 30° - 50°C
- $T_{\text{cond}}$: 70° - 80°C
- $P_{\text{abs}}$: 0.1 – 0.3 MPa
Results
Polish Pilot Plant

- $T_{\text{amb}}$: $0^\circ - 2.4^\circ C$
- $Q_{\text{heat}}$: 39 kW
- $P_{\text{in}}$: 7.1 kW
- COP: 5.5
- $\eta_{\text{isentropic}}$: 68%
- $T_{\text{out max}}$: 82°C
Projects in Process Heating

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Thermal Energy Storage for Medium Temperature Industrial Process Heating

- Materials Update
- System Update
- System Performance
## Materials

### Table 1 Potential molten salt mixture as medium temperature heat storage media

<table>
<thead>
<tr>
<th>PCMs</th>
<th>Melting temperature (°C)</th>
<th>Latent heat (kJ/kg)</th>
<th>Price ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnCl₂ - NaCl - KCl</td>
<td>203</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaOH - Na₂CO₃</td>
<td>210</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KNO₃ (54wt%) - NaNO₃ (46wt%)</td>
<td>222</td>
<td>161</td>
<td>~0.62</td>
</tr>
<tr>
<td>NaNO₃ - NaNO₂</td>
<td>226-233</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca(NO₃)₂ (45wt%) - NaNO₃ (55wt%)</td>
<td>230</td>
<td>~110</td>
<td>~0.33</td>
</tr>
<tr>
<td>Ca(NO₃)₂ - NaNO₂</td>
<td>200-223</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca(NO₃)₁₂ - LiNO₃</td>
<td>235</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiNO₃ (12wt%) - NaNO₃ (18wt%) - KNO₃ (70wt%)</td>
<td>200</td>
<td></td>
<td>~1.84</td>
</tr>
<tr>
<td>LiNO₃ (57wt%) - NaNO₃ (43wt%)</td>
<td>193</td>
<td>248</td>
<td>~5.8</td>
</tr>
<tr>
<td>LiNO₃ (49wt%) - NaNO₃ (51wt%)</td>
<td>194</td>
<td>265</td>
<td>~5.1</td>
</tr>
<tr>
<td>LiNO₃ (87wt%) - NaCl (13wt%)</td>
<td>208</td>
<td>360</td>
<td>~8.7</td>
</tr>
<tr>
<td>LiNO₃ (45wt%) - NaNO₃ (47wt%) - Sr(NO₃)₂ (8wt%)</td>
<td>200</td>
<td>199</td>
<td>~4.9</td>
</tr>
</tbody>
</table>

### Table 2 Market prices of some salts

<table>
<thead>
<tr>
<th>Salt</th>
<th>Price (per Metric Ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca(NO₃)₂</td>
<td>$250 ~ $280</td>
</tr>
<tr>
<td>NaNO₃</td>
<td>$300 ~ $500</td>
</tr>
<tr>
<td>KNO₃</td>
<td>$700 ~ $900</td>
</tr>
<tr>
<td>LiNO₃</td>
<td>Around $10,000</td>
</tr>
<tr>
<td>NaNO₂</td>
<td>$400 ~ $500</td>
</tr>
<tr>
<td>NaCl</td>
<td>$50 ~ $100</td>
</tr>
<tr>
<td>ZnCl₂</td>
<td>$950 ~ $1000</td>
</tr>
<tr>
<td>KCl</td>
<td>$500 ~ $900</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>$180 ~ $250</td>
</tr>
<tr>
<td>Sr(NO₃)₂</td>
<td>Around $3,000</td>
</tr>
<tr>
<td>NaOH</td>
<td>$350 ~ $450</td>
</tr>
</tbody>
</table>

Material investigations contain two parts:

1. Research stage
   1) Binary system with lithium nitrate
   2) Ternary system of LiNO₃ (12wt%) - NaNO₃ (18wt%) - KNO₃ (70wt%)

2. Industrial application stage
   1) KNO₃ (54wt%) - NaNO₃ (46wt%)
   2) Ca(NO₃)₂ (45wt%) - NaNO₃ (55wt%)
   3) Ternary system of LiNO₃ (12wt%) - NaNO₃ (18wt%) - KNO₃ (70wt%)
   4) Other new ternary or quaternary systems
Binary system with lithium nitrate (Research stage)

LiNO$_3$(87wt%) - NaCl(13wt%)

LiNO$_3$(57wt%) - NaNO$_3$(43wt%)

Ca(NO$_3$)$_2$ - LiNO$_3$ (To be tested...)
Heat storage system

Double pipes heat exchanger: heat transfer pipe can be smoothed pipe or enhanced pipes
Outside pipe diameter $D_o$: 50 mm
Inside pipe diameter $D_{in}$: 20 mm
Pipe length: 1 m
New thermal storage test facilities at Warwick and Loughborough
ThermExS Lab – now under construction

Warwick:
  4 Heat sources/sinks up to 30kW, -20 to 300°C
  Switching and controlled pumping to:
  • 4 sorption / chemical reactors
  • 2 ammonia evaporator / condensers
  • 2 steam evaporator / condensers
  • External equipment via pressurised water loop

The purpose of the facility is to dramatically reduce the time
needed to test new concepts in thermal storage,
transformation, heat pumping etc by providing a uniquely
flexible fully instrumented test rig.
Test Facilities

• ‘ThermExS Lab ’
  Thermal storage test facility under construction.
• Will also be used as a heat source and sink for testing of the heat pump.
• Expected to be completed in the next few months.
Test Facilities

- ‘ThermExS Lab’, Thermal storage test facility under construction.
- Will also be used as a heat source and sink for testing of the heat pump.
- Expected to be completed in the next few months.

Some understandable examples to give an idea of the new sorts of toy we could play with…
1-salt thermal store (c. 2 MJ/litre)

Phase 1: Storage of heat at 200°C

Phase 2: Discharge of heat at 200°C
**Rationale:** Industrial processes commonly reject heat at temperatures of 90°C or higher that cannot be utilised close to their source. A thermal transformer can transform some of this heat to higher useful temperatures, rejecting the remainder at close to ambient.

**Challenges:** Identifying suitable economically viable major processes that would benefit. Identifying physical or chemical reactions best suited to the major needs.

**Deliverables:** Identification of process needs and matching reactions with potentially high efficiency. Construction of laboratory PoC to investigate heat and mass transfer limitations.

- **3kW 120°C** for steam raising
- **10kW 90°C** from waste heat
- **7kW 50°C** rejected heat
1-salt thermal transformer

Phase 1: Storage of heat at 90°C

Desorption at low pressure

Heat in at 90°C

Salt 1

Condenser

Heat out at 30°

Adsorption at high pressure

Heat in at 90°C

Evaporator

Heat out at 120°C

Phase 2: Discharge of heat at 120°C

Heat out (120°)/Heat in (90°) = 0.35 ?
Phase 1: Storage of heat at 90°C

Phase 2: Discharge of heat at 120°C

2-salt thermal transformer

Desorption at low pressure

Heat out at 120°C

Heat in at 90°C

Heat out at 30°C

Adsorption at high pressure
Summary

i-STUTE is a collaboration of engineering, business and behavioural experts looking for sound, economic, acceptable solutions for the supply of heating and cooling.

Our projects include:

<table>
<thead>
<tr>
<th>Task</th>
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<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact chemical heat store</td>
<td>High temperature heat pumps</td>
<td>Supermarket refrigeration</td>
</tr>
<tr>
<td>Compact latent heat energy storage</td>
<td>Thermal transformers</td>
<td>Data Centre Cooling</td>
</tr>
<tr>
<td>Advanced electric heat pump</td>
<td>Process heat Storage</td>
<td>Refrigerated transport</td>
</tr>
<tr>
<td>Next generation gas powered heat pump</td>
<td></td>
<td>Integrated heating and cooling</td>
</tr>
<tr>
<td>Heat emitter study</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Summary

The future of heating probably involves ALL of:

- Electric heat pumps
- Gas heat pumps
- Smart controls
- Storage
- Micro CHP
- Fuel cells
- Innovative business models

Plus things we have not thought of yet, integrated but affordable, used appropriately, appealing to the customer. No pressure…
Thank you!

Questions???