The Dearman Engine in a Future Powertrain

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Pressure on environmental performance will not relent – cost-effective solutions are needed

Batteries and fuel cells provide zero emissions at point of use – but...

- Capital cost high – payback can exist but it may be long, and risk-averse markets do not welcome CapEx
- Life-cycle credentials can be diminished by “exotic” materials
- Batteries take time to recharge, fuel cells need a Hydrogen infrastructure

The Dearman Engine is an efficient Rankine-cycle expander powered by waste heat and liquid Nitrogen (LiN) or air (LiAir)

- Simple – made from common, recyclable metals and plastics
- Cheap – cost similar to ICE
- Existing infrastructure – LiN is a commonly used industrial gas

Can the Dearman Engine compete in a vehicle powertrain?
**The Dearman Engine**

**Unpackaging Power and Cold**

**Process** – Operates by boiling liquid air or nitrogen to produce high pressure gas that can be used to do work. **Power + cooling**

**Inventive Step** Heat transfer inside the cylinder through direct contact heat exchange with a heat exchange fluid – **patent granted**

- Rapid expansion
- High pressurisation rates
- Near isothermal expansion
- Non combustive

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**Return Stroke**
Warm heat exchange fluid (HEF) enters the cylinder.

**Top Dead Centre**
Air injected - comes into contact with the HEF causes rapid temperature rise.

**Power Stroke**
The air expands pushing the piston down. Direct contact heat transfer continues allowing near isothermal expansion.

**Bottom Dead Centre**
The exhaust mixture leaves the cylinder. The gas is returned to the atmosphere and the HEF is re-heated and re-used.

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*Theoretical maximum specific exergy available from LiN is ~214Wh/kg. Liquefaction requires ~400Wh/kg but is performed using offpeak energy.*

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Benefits of the Dearman Engine

<table>
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<tr>
<th>Characteristics</th>
<th>Advantages</th>
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<tbody>
<tr>
<td>• Made from simple materials in well-established processes</td>
<td>• Low capital cost</td>
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<td>• Can use waste heat to boost efficiency, even at low temperatures</td>
<td>• Fits established ICE manufacturing base</td>
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<td>• Fuel non-combustible, exhaust cool and clean</td>
<td>• Potential for plastics, additive manufacture</td>
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<td>• Liquid air or N₂ widely produced and available</td>
<td>• Low life cycle impacts</td>
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<td>• Waste heat (i.e. inefficiency) is a problem for engines, and fuel cells</td>
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<td>• Works alongside other technologies rather than seeking to replace them</td>
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<td>• Synergies with cooling applications</td>
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<td>• Indoor and underground use possible</td>
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<td>• Low heat signature</td>
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<td>• Modest infrastructure requirement</td>
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<td>• Opportunity to integrate at system level with renewable energy to achieve zero CO₂</td>
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A simple, first generation engine has proved the technology in the lab and refrigeration

- Single cylinder prototype engines running since early 2014:
  - Total run time >300hrs
  - One engine ~170 hrs
  - Polytropic Index of 1.15 (vs Isothermal 1.0 & Adiabatic 1.4) indicates HEF working
- Two further units now in service
  - Refrigeration mule – IDP8 Cool-E project with MIRA, Air Products & Loughborough Uni, running Feb 2015
  - Tribology research at University of Birmingham

- **Learning from this work is informing the design of an improved second generation for refrigeration field trials**
Refrigeration is a natural application – uses synergy with a conventional vapour cycle

- Dearman Engine delivers chilling via LiN vapourisation
- Power operates generator for fans & defrosting – but surplus power drives a small vapour-cycle ‘fridge
- Heat from condenser harvested to warm the HEF – good synergy

Predicted performance (2nd generation)
>140Wh chilling per kg LiN in a frozen TRU application – payback vs competition, zero emissions
Required engine efficiency depends on cold-to-power ratio of its use

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<tr>
<th>Application</th>
<th>TRU for HGV</th>
<th>Cold + Power APU</th>
<th>WHR + AC for Bus</th>
<th>WHR no AC for Bus</th>
<th>Small vehicle power</th>
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<tbody>
<tr>
<td>Engine LiN consumption for robust return, Wh/kg</td>
<td>~30</td>
<td>40-60</td>
<td>&gt;60</td>
<td>~100</td>
<td>&gt;100</td>
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- Pure Cold
- Cold with power surplus
- Power with Cold surplus
- Pure power as assist
- Pure power as prime mover

- A significant step in efficiency is required to make the technology robustly attractive in applications where power, not cold, is the dominant requirement.
- However, this step does not require any laws of thermodynamics to be broken!
How to improve efficiency – many options, route chosen is low risk, has precedent

Options for improved efficiency

• **Improved HEF heat transfer** – shown by thermodynamic analysis to offer significant theoretical potential, but realistic limits unknown

• **Reduced friction and parasitics** – identified early in our development, but “low hanging fruit” already addressed

• **Shorter inlet valve opening** – to improve expansion ratio; challenging, as we were already using valve periods down to 25° crank

• **Multiple expansion stages** – preferred route
  • Proven in steam cycles, benefit could be quantified
  • Allows working pressure increase from ~40bar to 100bar
  • Re-heat possible to complement the action of HEF
  • Compatible with existing piston / poppet-valve architecture
A concept has been developed in simulation – hardware realisation in 2015

Concept study approach
• Validated 1-d model, embracing:
  • Gas dynamics and valve-port efficiencies
  • In cylinder thermodynamics
  • Friction and parasitic work (LiN & HEF pumping)
  • Sealing & leakage
  • Torque pulses
• Parametric studies
  • Engine size and speed
  • Cylinder count and bore size
  • Valve timing – IVC, EVO

High Efficiency Engine
• 4.5l, 40kW@1000rev/min
• 64Wh/kg LiN net of ancillaries
First implementation is a “heat hybrid” system, assisting the ICE in a bus

**Operating principle**
- DE harvests ICE heat, assists it
- ICE is downsized (e.g. 6 to 4cyl), and operates closer to eye of BSFC map, less transiently
- DE is used in short bursts, e.g. launch and acceleration; also possible to shut down ICE and provide low power levels by DE
- Energy stored in coolant thermal inertia

**CE-POWER project**
- InnovateUK project - partnership with MIRA, Air Products, CenEx, TRL, Productiv & MTC
- Technology & manufacturing advancement – demo bus in 2016
- Aiming to demonstrate payback in 3-5 years in UK; better in hot climates
Dearman Engine is an attractive device for using LiN or LiAir as a zero-emission energy vector

- The Dearman Engine is establishing itself as an attractive device for providing **cold and power**
  - A high efficiency Dearman Engine concept demonstrates that its use can be extended into **power-only applications**
- The technology is **complementary to the ICE** (as it uses its waste heat and allows it to be right-sized)
  - The same complementarity applies to **fuel cells** (which reject more heat than ICEs), and even **battery-electric** systems (with a small, Dearman APU)
- Similar levels of efficiency also allow use in **small urban ZEVS**
- The **energy chain** (air liquefaction and separation) is highly complementary with future energy trends
  - Rising renewables – **demand-side management**
  - LNG import – use of “**waste cold**” from re-gasification