Ultra High Efficiency Powertrain

A Joint EPSRC / APC Workshop held at the University of Brighton Advanced Engineering Centre, 21th December 2016

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ICE Thermal Efficiency Spoke

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1. Introduction

On 21st December 2016, a workshop was held at the University of Brighton to discuss and build consensus on the future of high efficiency thermal propulsion technology for road transport. The objectives of the workshop were to debate the following questions:

What is the role of the ICE in future transport propulsion systems?

What does a clean, efficient liquid fuelled powertrain look like?

What are the research challenges in delivering such a powertrain?

The workshop was aimed at the right hand side of the Auto Council roadmaps in the 2030-2050 time horizon – looking beyond conventional internal combustion engines to efficient, clean 'thermal propulsion systems' (TPS). The workshop was supported jointly by the EPSRC Ultra Efficient Engines project and the APC.

2. Organisation of the Workshop

The workshop was run under Chatham house rules over three sessions. In each session, three broad vehicle applications were considered by the group, recognising the difference in journey energy requirement and in the context of the relative strengths and weaknesses of alternative propulsion technologies such as all battery-electric and fuel cell powered vehicles:

- Urban transport
- Medium range light payload (LCV and passenger car)
- Long haul freight

Bus was not considered as a discreet area due to the smaller relative size of this sector and overlap in technology requirements with the three applications identified. The session looked each in turn at the following questions:

- What are the potential future ultra-efficient powertrain technologies
- What are the research needs for ultra-efficient powertrain technology
- What is the role of APC, the spokes, EPSRC and innovate UK

The focus of the workshop was on liquid fuel only, this was qualified during the workshop as meaning 'not hydrogen' and so gaseous carbon based fuels were considered (eg methane).

3. Session 1: What are potential future ultra-efficient powertrain technologies

3.1 Urban transport

The overarching theme identified for this sector was integration of the complete powertrain. i.e., optimisation of the transmission, electrical system, energy storage (such as advanced KERS), engine and the thermal system for all components (e.g. the cooling of the thermal propulsion system, transmission and electrical sub-system) together. There was consensus that the powertrain would need to be less flexible, driven by electrical system integration and so would be optimised for a narrower operating range, opening opportunities to improve efficiency and reduce emissions. The question of how a thermal propulsion system can be fully sustainable in the long term was raised. It was agreed a robust full life cycle assessment methodology is required to properly identify true sustainable technologies. A number of technology themes were identified. Several themes were developed during the workshop.

Engine (TPS) Optimisation

As mentioned above, the future TPS would be optimised for a narrower range of conditions with less transient demand, enabled by electrification of the powertrain. Zero NOx emissions were also seen as essential. Key areas identified were:

- More downsized engines - fewer cylinders, particularly for smaller vehicles, possibly single cylinder engines, driving requirements for new turbocharging technology.
- Zero NOx combustion - enabled by HCCI combustion strategies and reduced transient demand. Measures such as water injection, possibly supplied from AC condensate could also play a role.
- More use of cylinder deactivation, requiring development of the lubrication system and thermal system to enable this feature.
- Flexible active control, for common propulsion system platforms operating on different platforms in different market segments.

It was felt there would continue to be a requirement for higher power density, towards 200kW/l.

Fuels

The consensus view was that future fuels would be very different from those in use today, but there was not a clear view on what fuels would be used due to the impact of external factors such as how the rest of the energy system might develop and requirements of autonomous vehicles. Issues discussed were:

- A possible trend to low octane gaseous fuels
- More integration of transport with other parts of the energy system to improve whole system efficiency e.g. use of methane, captured from city waste in municipal vehicles
- Common sustainable aerospace and road transport fuels to achieve scale and reduce cost
- Fuels that can be reformed on vehicle at low temperatures (for waste heat recovery and fuel cells)
- Possibly less refined fuels, reducing the production cost of making a sustainable fuel requiring thermal propulsion systems tolerant to more variability in the fuel

Materials

Improved materials were seen as an important enabler for TPS, such as bearings for long periods of zero use and stop start operation:

- Temperature swing materials for reduced combustion chamber heat loss
- Very high temperature materials (1050ºC plus) for exhaust systems
- Low friction materials to remove the need for a lubrication system

Technology Disruptors

In this application, the view was that a fundamental change to the thermodynamics of the thermal propulsion system was unlikely as the benefits of system integration would deliver significant improvements. However, two potential disruptive technologies were identified

- Downsized dual cycle gas turbine
- Free piston with integrated linear generator

3.2 Medium range light payload

As with urban transport, the absolute requirement of zero emissions combustion was identified. In this sector, changes in how transport is accessed and used by the consumer were seen as important factors in defining technology requirements. Changes such as the introduction of smart roads, vehicle platooning, road pricing and changing vehicle ownership models were all seen as potential drivers for different technical solutions. Electrification technology developed for urban transport would migrate to this sector, with ZEV capability being enabled by the electric components of the powertrain. Finally, legislation was seen as a key driver, in particular any legislation that mandated the use of all electric solutions. Key themes identified were:

Architecture

More fundamental changes to the engine architecture were contemplated for this application than in urban transportation. This was driven by the competitive advantage of a chemically (rather than electrically) fuelled propulsion system in the range – cost – weight trade off. It was agreed there would be choices in the architecture, between a large complex high efficiency engine with a small electrical system versus a small compact high power specific power engine acting as a range extender for a highly electrified drivetrain. The above mentioned impact external factors would influence the preferred solution, but it was also considered likely both solutions could be present in the market.

- ‘Dual powertrain’, with ICE sized for average road load and electric drive to manage transient capability
- For a high efficiency engine with a less electrified drive, geometric flexibility, starting with variable compression ratio moving to a ‘variable geometry engine’ was considered
- Integrated waste heat recovery to improve efficiency through low thermal loss engines, thermo-acoustic, waste heat to cold, waste heat to electricity

Fuels

As with the urban application, evolution of the fuel was seen as inevitable and all the comments made for urban transport were seen as relevant to this application. The key question was: ‘What will be the low carbon sustainable fuel of the future?’. To really exploit the benefits of TPS technology over a hydrogen fuel cell, the fuel would not be hydrogen but an alternative carrier for hydrogen (such as carbon sequestrated methane).

Disruptive technologies and thermodynamics cycles

There was a consensus view that there was more opportunity for disruptive thermal propulsion technologies to deliver benefit to this application than in urban transport. Potential technologies discussed included:

- Inverted Brayton cycle
- Split cycle
- Solid Oxide Fuel Cells (SOFC)
- Closed engine cycles, such as the argon cycle
- Split cycle integrated with SOFC
- Very high peak pressure (>300bar) including double expansion cycles
- On board carbon capture
- Membrane gas separation, from the inlet air to change oxygen / nitrogen concentrations and from the exhaust to capture carbon dioxide and/or water
- Material breakthrough (eg ‘graphene’) – there was a consensus that some breakthrough in material technology would come but what the breakthrough might be and what impact it would have was unclear!

3.3 Heavy Duty

There was a consensus view that deep electrification of the powertrain was unlikely in this application as there is less benefit that in other applications and the problem of on board electric energy storage was fundamental and unlikely to be solved even in the long term. However, electrification of the highways could be a major disruptor and would enable displacement of TPS technology with a mainly electric solution. It was commented that in the UK, journey distances were not that long compared to other markets but as a ‘UK centric’ solution was unlikely, other geographic market requirements may dominate the technology solution. It was also agreed the roadmap should be renamed thermal propulsion rather than IC engine. There was not a specific discussion on fuels in this application, but it was agreed the comments made for the medium range application applied to this sector.

More disruptive changes to the thermal propulsion system were considered very likely in this application in the following areas:

Exhaust Heat Recovery

Exhaust waste heat recovery was considered essential for future efficiency improvement but there was not a clear technological solution at this stage. Options include:

- Fuel reforming
- Advanced TEG
- Increase high grade / reduce low grade heat through low temperature combustion and / or in cylinder insulation (adiabatic engine)

- Use of cryogenic fluids, from fuel (LNG) or on board liquid storage (liquid air or nitrogen) for enhanced waste heat recovery

New highly efficient thermodynamic cycles

The application of new thermodynamic cycles was seen as a definite possibility in this sector, but again the exact technology solution was unclear. Options include:

- Heating and cooling cycles
- Multi phase and multi state working fluids
- Integration of heat engines with solid oxide fuel cells
- Dual fuel injection cycles (such as gas and liquid fuel)
- Split cycle (with recuperator for waste heat recovery)
- Open thermal cycle combined with closed Stirling cycle
- Recuperated gas turbines

Emissions Control

Advances in toxic emissions control and possible on board carbon capture were potential new technologies that could enter the market. Unlike in medium range smaller vehicles, achieving limited ZEV range with a battery was less attractive. Options considered include:

- Nitrogen capturing additives in fuel
- Nitrogen scrubbers
- Air separation + EGR NOx control
- Passive aftertreatment
- In cylinder catalysis
- CO_2 capture on vehicle, such as scrubbers in the exhaust
- Combined heat recovery with aftertreatment

Radical Disruptors

- Cross over from space propulsion, such as ion drive
- Electrification of the road
- Major breakthrough in fuel cell technology

4. Session 2: What are the research needs for ultra efficient powertrain technology

Themes identified during the previous session were ranked by impact, challenge and then the most important 5 themes were highlighted (shown in bold in the tables below).

4.1 Urban transport

	Impact (L-H)		
Challenge (L-H)		**5. Low temperature fuel reforming** HCCI (including variants off) Single cylinder for A class cars (turbocharging) HCCI optimised two stroke	**1.Temperature swing materials** Very high temperature materials for exhaust systems Crank deactivation Low friction materials to remove the lubrication system Bearing systems for long periods of zero use Free piston with linear generator
		3. Thermal systems integration for all components in a hybrid / battery system **4. Water injection using water from tank, exhaust condensate or AC condensate** Common Aero and automotive fuels Application of NOx systems from diesel to allow lean burn gasoline	**2. Methods for widening the peak efficiency area of the operating map vs single high efficiency operating point** Integration of transmission elements with the engine Method for assessing through life efficiency and emissions
	Lightweight structures Single piece castings, engine motor transmissions Engine change @200k miles Naturally aspirated (e-boost) powertrain Piece part reduction (sump integration etc) Cylinder deactivation	Advanced KERS Variable Compression Ratio Advanced valve train / valve less designs Octane on Demand Low Octane fuels ICE as an 'Air Cleaner'	

4.2 Medium range

	Impact (L-H)		
Challenge (L-H)		New Thermo Electric materials Geometric flexibility (beyond VCR)	**1. Impact of changes in society** **2. Fast, validated, predictive models** **5. Low carbon sustainable fuels** Advanced FIE
		3. Training & Skills Advanced transmissions Lightweight materials Residue free emissions control systems and fuels	
			4. Retrofit of technology into fleet (research challenge - how this could be done)

4.3 Heavy Duty

	Impact (L-H)		
Challenge (L-H)	Increased energy density fuels	Integration of electrochemical and thermodynamic cycles High efficiency IVT	**Zero NOx combustion** **70% thermal efficient** **Zero lifetime carbon sustainable liquid fuels (CO_2 capture from air)**
	Low grade waste heat recovery NVH in urban areas	Improving efficiency from cryogenic fuels Effective explanation of the science base around phenomena such as combustion, emissions formation tribology etc.	Zero NOx systems (engine + aftertreatment <1ppm) **60% thermal efficiency**
		55% thermal efficiency	

There was not clear ranking of priority from the heavy duty discussion but three priority areas were identified. Efficiency targets of 55%, 60% and 70% were discussed. While these targets were largely arbitrary, the rationale behind their selection is described below:

- 55% - Stretch target with relatively conventional combustion and waste heat recovery

- 60% - Stretch target with TPS thermodynamic concepts that are in development (such as split cycle) and competitive with a fuel cell
- 70% - Game changing target requiring new breakthrough thermodynamic concepts

6. Session 3: What is the role of APC, the spokes, EPSRC and innovate UK

The overall structure of Research and Development in the UK was seen as a strength. For all funding agencies, research and development of sustainable fuels and advanced materials were seen as priorities. It was noted that material research should not exclusively cover light weighting, but should include enablers for new propulsion technology such as low cost, high temperature resistant materials.

APC / Spoke Network

The promotion of better system thinking on how component and sub systems are optimised and integrated together was seen as essential. The APC spoke network should therefore ensure the communities do not become siloed and work together. It was noted that the spokes were working closely together and this will help integrate the various communities, facilitating collaboration at system level.

It was noted there was not a fuel spoke or fuel cell spoke. Given the importance of sustainable fuels as part of the energy mix, this must be addressed. It was suggested the two internal combustion engine spokes could support this by reaching out to groups in relevant areas such as fuel chemistry, production and energy system research.

It was also noted there is not a spoke supporting fuel cells. It was suggested solid oxide fuel cells, in terms of the thermal management and sustainable fuels challenges, could fit within the scope two internal combustion engine spokes.

EPSRC / R-UK

For EPSRC, supporting the development of the spoke network through a challenge network or similar instrument was seen as essential. Given the comments above, the challenge network should focus on bringing the spoke academic communities together and linking with other communities, such as fuel chemistry and energy research rather than simply supporting the specific technology areas.

7. Key Actions Points

Changes in Personal Transport

Understanding the impact technological change in other sectors and broader societal changes might have was a critical issue that will impact the requirements of future propulsion systems. It was agreed the spoke community should engage with RC-UK and behavioural research groups to define an appropriate study to address this knowledge gap.

Fuels & Energy

The lack of a coordinated approach to the introduction of sustainable fuel into the transport system and the integration of the transport system with a broader low carbon energy system needs to be addressed. It was agreed that APC and the ICE spokes should discuss how this should be addressed and present back to the UK Automotive Council.

And finally, we must talk in terms of **Thermal propulsion** not ICE!