Introduction to Engines and Fuels for Future Transport

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Abstract: Global transport is almost entirely powered by internal combustion engines (ICEs) and petroleum-derived liquid fuels. Currently, there are many efforts to move transport away from this energy system to reduce the overall carbon footprint. In addition, tailpipe emissions from ICEs have to meet increasingly stringent standards. However, all the alternatives, such as battery electric vehicles (BEVs), start from a very low base and face serious barriers to unlimited and fast expansion and cannot completely displace ICEs for several decades to come. Hence it is also important to continue to improve ICEs to ensure the sustainability of transport. This volume considers some of these approaches, sustainable fuels, and methodologies like life cycle analysis (LCA) needed to assess the true impact of alternative approaches to power transport. This chapter provides brief descriptions of the fourteen chapters that follow.

Keywords: Internal Combustion Engines, Fuels, Life Cycle Analysis, Hybrid Engines, Methanol, Ammonia.

Modern societies depend critically on transport and mobility. Currently, internal combustion engines (ICEs) power 99.8% of global transport, and petroleum-based liquid fuels account for around 95% of global transport energy. The demand for global transport energy is extremely large, with *daily* demand for liquid fuels alone being around 11.5 billion litres [1, 2]. Currently, the world has around 1.3 billion light-duty vehicles (LDVs) and 380 million heavy-duty vehicles (HDVs), but LDVs account for nearly 45% of global transport energy [1, 2]. In the next 20-30 years, the worldwide demand for transport is expected to increase primarily in the non-OECD countries. There are great efforts and many initiatives to reduce the carbon footprint of transport and tailpipe emissions that have to meet increasingly stringent standards. Transport energy is expected, on current trends, to still come substantially (>80-90% by 2040) from petroleum-based fuels because alternatives such as electric vehicles and sustainable fuels start from a negligible base and cannot grow fast enough or without constraints [1, 2]. There is also significant scope for improving the efficiency and environmental impact of ICEs [5, 6]. Indeed, the sustainability of the global transport sector cannot be ensured without improving the internal combustion engines, though alternatives such as battery electric vehicles (BEVs) will undoubtedly increase [1-6]. All available technologies have to be sensibly deployed and continuously improved to maintain the sustainability of transport – the future is eclectic [3]. It is also important that all the technologies need to be assessed honestly on a life cycle basis to ensure that the claimed benefits are actually delivered, and the greenhouse gas (GHG) emissions and health impacts are not simply displaced elsewhere, from where the vehicle is used.

This book has fourteen chapters, mostly authoritative reviews from the legends in the field, addressing various aspects of developments in this field. This chapter gives a brief overview of these chapters.

The second chapter – "**Sustainable Transport**" – discusses many of these themes and makes a case for a fact-driven, decisive approach, keeping multiple options open. It calls for a diverse mix of low-carbon technologies to be pursued rather than betting on a single technology like battery electric vehicles – an eclectic future.

Minimising the tailpipe emissions is as important as reducing the GHG impact of transport. Indeed, vehicles have to meet increasingly stringent emissions regulations to be allowed to operate. The third chapter, "**A review of emissions control technologies for on-road vehicles**", addresses this essential aspect of vehicle and engine technology. It makes the interesting point that attention is shifting to other emissions sources such as brake and tire wear, signalling that the battle against tailpipe emissions is nearly won.

Opposed Piston (OP) engines offer the prospect of very high efficiency and near-zero levels of criteria emissions with conventional after-treatment system configurations. The fourth chapter, **"Opposed-Piston Engine Renaissance: Low CO_2 and Criteria Emissions"**, provides an overview of OP engine design characteristics and summarises actual test results for heavy-duty diesel engines while using conventional underfloor after-treatment systems (DOC/ DPF/ SCR/ ASC). The results show peak brake thermal efficiency greater than 49%; engine-out soot 75% lower than a benchmark 15L four-stroke conventional engine; tailpipe NO_x 96% lower than 2020 EPA regulations; 65% lower than California's 2027 ultra-low NO_x regulation (on the FTP cycle).

The fifth chapter, "**An Overview of Hybrid Electric Vehicle Technology**", reviews another extremely important approach to improving transport sustainability through partial electrification, promising improvements in fuel consumption and emission rates with a performance comparable to the conventional vehicles. The performance of a hybrid electric vehicle (HEV) depends on the powertrain type, components configuration and energy management strategy (EMS). This chapter presents an overview of essential components used in HEVs, including the energy storage system (i.e. the battery, super-capacitor, and fuel cell), electric motors, and DC-DC/ DC-AC converters and their size/ capacity optimisation. It also discusses emissions of HEVs under actual operating conditions and key issues and challenges of HEV technology.

The sixth chapter, “**Life-Cycle Analysis for the Automotive Sector**”, addresses an extremely important aspect that regulators and policy makers currently ignore in choosing the optimum technology to minimise GHG emissions. For instance, for battery electric vehicles (BEVs), mining for raw materials and then manufacturing them into vehicle and powertrain components create embedded emissions. Production of fuel or electricity generates emissions, and the vehicle end-of-life also impacts total emissions depending on scrappage or recycling processes. To accurately account for these stages, a life-cycle analysis (LCA) is required. The chapter reviews several LCA studies and identifies commonly used assumptions, variations on assumptions, and their impact on conclusions. Finally, a set of recommendations for future LCA work is presented.

The seventh chapter, “**Pre-Chamber Combustors: An Enabling Technology for High Efficiency, Low CO_2 Engine Operation**”, discusses a promising approach to ignite dilute/ lean mixtures in engines to improve efficiency. It examines applications and benefits of pre-chambers, including knock reduction in high specific output downsized engines and lean limit extension in high-efficiency engines. Fundamental barriers to pre-chamber engine adoption are discussed. Amongst the topics addressed: pre-chamber geometry optimisation that spans the full engine map, in-pre-chamber mixture preparation, low load and idle stability and ensuring sufficient spark retard for catalyst light-off. Pre-chamber engines can also be ideal platforms for future fuels, including low carbon fuels such as hydrogen with highly specific operating requirements. The role of the pre-chamber engine in future transport and its potential for facilitating significant decarbonisation of the sector is discussed.

The eighth chapter, “ **Pathway to Ultra-Lean IC engine combustion: Narrow Throat Pre-chamber**”, continues with this theme. A narrow throat pre-chamber as an ignition source allows extending the lean limit through a robust multi reactive jet ignition and in-cylinder turbulence generation. Metal engine studies coupled with optical engine studies involving high-speed visualisation and laser diagnostics offer a better understanding of this combustion mode. This chapter evaluates and summarises recent advances in pre-chamber combustion research.

The ninth chapter, “**Active Pre-Chamber with Bio-Hybrid Fuels**”, describes a research study using the bio-hybrid fuels DME and ethyl acetate in an active pre-chamber system. Single-cylinder engine experiments are coupled with optical diagnostics and numerical modelling to understand the combustion process. Additional optical experiments on a rapid compression machine provide insights into the ignition inside the pre-chamber and the subsequent combustion in the main chamber.

Ammonia is being studied as a carbon-free fuel for internal combustion engines. Ammonia has a higher volumetric energy density than gasoline and is easier to produce, store, and transport than other carbon-free fuels. However, ammonia-fueled applications exhibit lower efficiency and stability than conventional-fueled systems due to ammonia’s lower flame speed and combustion temperatures. Chapter 10, “**The Use of Ammonia as a Fuel for Combustion Engines**” and Chapter 11, “**Ammonia as fuel**

for transportation to mitigate zero carbon impact", both review previous and ongoing studies, exploring the potential of ammonia as an ICE fuel. The literature where ammonia has been used on its own or with other fuels in SI, CI and HCCI engines is reviewed. The strategies to overcome the shortcomings of ammonia as an engine fuel are discussed.

Chapter 12, "**Methanol as Fuel for Internal Combustion Engine**", is a comprehensive review of methanol as an ICE fuel. It covers the production of methanol and the well-to-wheel GHG emissions of different approaches to producing methanol. It reviews the history of methanol engines, stretching back over 100 years, and methanol on its own and with other fuels in ICE. The advantages and disadvantages of methanol as an engine fuel are discussed, and the need for road testing in practical modern engines is identified.

Chapter 13, "**Technologies for knock mitigation in SI engines – a review**", reviews the literature on strategies used to overcome knock, limiting SI engine efficiency. Optimised combustion chamber geometry shapes and combinations of methodologies have been proposed for a reduced combustion time, water injection, cooled exhaust gas recirculation, and changes in the engine cooling systems have been applied to enhance end gas cooling, are some of the methods used to mitigate knock. The use of knock resistant fuels such as alcohols are also discussed.

Knock onset is determined by chemical kinetics of the fuel-air mixture ahead of the flame front as it is subjected to increasing pressure and temperature during the engine cycle. Reliable chemical kinetic models greatly assist the prediction of knock onset. However, practical fuels are too complex for such models to be developed, and simple surrogates, which can be more accurately modelled but are good substitutes for actual gasoline, are needed. Chapter 14, "**Explicit equations for designing surrogate gasoline formulations containing toluene, n-heptane and iso-pentane**", describes the development of one such surrogate.

Finally, Chapter 15, " **Prediction of ignition modes in shock tubes relevant to engine Conditions**" describes a theoretical approach to the prediction of ignition modes in shock tubes. This is relevant to understanding pre-ignition in SI engines which can lead to very high knock intensities in downsized, turbocharged SI engines and limits this approach to improving SI engine efficiency.

We hope readers interested in transport, mobility, internal combustion engines, and new fuels find this collection of mostly review articles a useful resource.

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