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Developments in internal combustion engines and implications for combustion science and future transport fuels

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Abstract

Changes in engine technology, driven by the need to increase the efficiency of the SI engine and reduce NOx and soot from diesel engines, and in transport energy demand will have a profound effect on the properties, specifications and production of future fuels. The expected increase in global demand for transport energy is significantly skewed towards heavier fuels like jet fuel and diesel compared to gasoline. Abnormal combustion such as knock and preignition will become more likely as spark-ignition (SI) engines develop to become more efficient and fuel antiknock quality will become more important. In current and future SI engines, for a given RON (research octane number), a fuel of lower MON (motor octane number) has better antiknock quality. Current fuel specifications in several parts of the world assume that MON contributes to antiknock quality and will need to be revised as the mismatch with engine requirements widens. Diesel engines need to maintain efficiency while reducing emissions of soot and NOx. Soot and NOx can be controlled more easily if such engines are run on fuels of extremely low cetane. In the long term compression ignition engines could run on fuels which require less processing in the refinery compared to today's fuels. Such an engine/fuel system could be significantly cheaper and also help mitigate the expected demand imbalance in favour of heavier fuels. The review concludes with a list of issues for combustion science that are relevant to this fuel and engine development.

Keywords: IC engines; Gasoline; Diesel; Autoignition; Preignition

Transport accounts for around 20% of the total energy consumed globally [1] and is of central importance to modern industrial society. The global demand for transport energy is expected to increase rapidly, by around 40% by 2040 compared to now, mostly in the non-OECD countries [2–5]. Transport is expected to be powered overwhelmingly (around 90% share) by Internal Combustion (IC) engines using liquid fuels made from petroleum (crude oil) in the foreseeable future, just as it is today, in spite of the expected advances in alternatives [2–5].

The supply and demand and the sources for transport energy as well as changes in engine design, and hence future fuels, are shaped factors

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such as energy security and by local and global environmental concerns such as climate change. In addition to legislative demands, future IC engines also have to respond to consumer demands for performance, drivability and affordability in an increasingly competitive world. Engine efficiency, performance and emissions will be squeezed to the utmost in the future and even small improvements, perhaps previously not considered worth pursuing, will become important. In such a context, traditional combustion problems such as ignition and flame development will acquire renewed importance. As engine designs change problems such as preignition leading to extremely heavy knock, "superknock", in SI engines are threatening to limit efficiency improvements. Other traditionally neglected fuel and combustion related issues such as deposit formation will also be important. However, the autoignition quality of fuels provides the major unifying thread to help understand how future fuels might be affected. This review discusses these issues – a more detailed discussion can be found in [2]. Engine technologies such as injector design and control strategies can affect mixing and hence combustion in diesel engines and are discussed in that context. Other engine and vehicle technologies such as friction reduction and transmission also affect fuel efficiency, performance and emissions but detailed discussion of such topics is beyond the scope of this review.

1. Internal combustion (IC) engines

IC engines are either spark ignition (SI) engines or compression ignition (CI) engines [6,7]. Heat release in SI engines occurs in an expanding turbulent flame in a premixed fuel/air mixture. In diesel engines heat release is initiated by autoignition as the fuel vaporizes and mixes with air. Diesel engines are more efficient than SI engines. However SI engines can use three-way catalysts to reduce emissions of hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NOx). Concern about soot emissions from SI engines is increasing though the levels of engine-out soot are very much lower compared to diesel engines. It is much more difficult to control emissions of soot and NOx, the major pollutants in diesel engines, through after-treatment of the exhaust. Diesel engines are more expensive compared to SI engines primarily because of the need to meet increasingly stringent regulations on soot and NOx emissions because this requires very high pressure injection systems and complex after treatment.

Homogeneous charge compression ignition (HCCI) engines have attracted recent attention because of the potential of high efficiency and low emissions operation. Heat release occurs in HCCI engines by autoignition of a *fully* premixed fuel/air mixture. The maximum load of HCCI engines is very limited and there is no in-cycle control of combustion phasing, making engine operation very difficult to control. It is very unlikely that there will be practical engines working in HCCI mode over the full operating range. However there is great scope for developing practical fuel/engine systems with "premixed enough" compression ignition to get most of the benefits of HCCI combustion – see Section 6.

The main driver in SI engine development is to improve their efficiency. For diesel engines the main driver is to meet increasingly stringent soot and NOx emissions requirements without compromising efficiency. All this has to be achieved at an acceptable cost and meet other customer demands. Fuel manufacture and development will be influenced by these engine development trends and will be constrained by factors affecting the supply and demand of transport energy.

2. Current transport fuels

Liquid fuels have evolved as the fuels of choice for transport because of their high energy density and the ease of transport, storage and handling. As a result an extensive global distribution network has been built up which is very difficult to replace or duplicate.

Transport fuels are mostly made in refineries starting with petroleum and then blending the products of several refinery processes [2,8]. Petroleum is first separated into different boiling range fractions by distillation. Liquid petroleum gas, LPG is made up of dissolved gases which are released when the temperature is increased above ambient and might constitute up to 2% of the crude. Its main component, around 75%, is propane. The fraction boiling roughly in the gasoline range from ~20 °C to ~200 °C that results from the initial distillation is termed 'straight run gasoline' (SRG). Products in this boiling range which can come from different processes in the refinery are termed 'naphtha'. Naphtha has to be processed further to improve its autoignition resistance before it is used as a gasoline component. The fraction in the boiling range of ~160 °C to ~380 °C is termed 'middle distillates'. Depending on the source of the crude, between 40% and 60% of the weight of petroleum can be "Residue" with boiling points above ~380 °C. These heavier fractions have to be converted through further processing into lighter fractions that can be used as fuel components. A description of refinery and other processes used for making fuel components can be found in Refs. [2,8,9].

In addition, other components made outside a conventional refinery are often used in liquid fuels These include biofuels such as ethanol, other oxy-