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Grand challenges in engine and automotive engineering

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Introduction

Oil provides 33% of the world's energy (Wilcox, 2014) and transportation engines account for over 60% of the 70 million barrels of crude used each day. Engines power the world's roughly one billion passenger vehicles, as well as trucks and heavy-duty vehicles. In the USA, engines consume 14 million barrels of oil per day or 2.5 gal/person. Since there are insufficient reserves, 62% is imported, and at current prices (e.g., $80 a barrel), the USA spends about 1 billion dollars a day on imported oil. This also impacts national security.

It is unreasonable to think that this vast consumption of fuel is sustainable. But prospects for replacing the IC engine with more fuel efficient and cleaner power plants are not hopeful. Indeed, a recent report (NRC, 2011) concluded that "...the internal combustion engine (ICE) will be the dominant prime mover for light-duty vehicles for many years, probably decades. Thus, it is clearly important to perform R&D to provide a better understanding of the fundamental processes affecting engine efficiency and the production of undesirable emissions." Also, there is no obvious alternative to the IC engine for medium- and heavy-duty commercial vehicles, which account for a quarter of all fuel used (mostly diesel).

The fuel used by IC engines also has a major impact on our global environment. Burning one 1 kg of fuel consumes about 15 kg of air, and significant energy is required to pump it into and out of the engine. In addition, about 3 kg of CO_2 is generated, which contributes to the world's annual production of 37 billion tons of CO_2, a major green house gas (GHG). Some fear that GHGs can cause climate change with unpredictable consequences. To address this problem, the International Energy Agency's roadmap is to reduce fuel use by 30–50% in new road vehicles worldwide by 2030, and in all vehicles by 2050 (IEA, 2012). Although 2050 appears distant, the time required to bring new engines to production, together with the years needed for new technology to permeate the vehicle fleet, means that major effort (and investment) will be required.

Thus, the grand challenge faced by engine and automotive engineering researchers over the next decades will be to devise technological advances that maximize engine efficiency, minimize pollutant emissions, and optimize tolerance to a wider variety of fuels in power generation and transportation systems.

Lessons from History – The Mayflower[1]

Much recent engine research has focused on improving the understanding of ignition, which is highly dependent on the fuel's chemical composition, and also on increasing the quality of the air–fuel mixture for improved combustion efficiency. However, this quest is by no means new. It is interesting

[1]Midgley and Kettering were inspired by the Mayflower (Massachusetts state flower), which blooms in early spring, even through a layer of snow. It was thought that the red color of the emerging leaves helps the plant absorb the sun's warmth.

to review the paths that have led to today's automotive engines. A starting point for discussion of engine efficiency is the theoretical air-standard Otto cycle efficiency, which indicates that engine efficiency increases with increased compression ratio. [Other parameters that also influence efficiency are described by Lavoie et al. (2012)]. Early spark ignition (SI) engines were plagued by "spark knock," which created explosive pressures that would damage engines and limited the compression ratio to about 4:1. Cylinder pressure measurements conducted as early as 1916[2] by Midgley and Kettering revealed, contrary to previous thought, that knocking was a pressure disturbance that came after the compressed charge had already been ignited, and was not due to "pre-ignition."

It was also discovered that different fuels exhibited different knock tendencies. In particular, kerosene knocked worse than gasoline, and the volatility difference between the fuels was thought to be the explanation (Boyd, 1950). To test the theory, minute amounts of a red dye (iodine) were added to kerosene in an attempt to make it absorb heat and vaporize better[1]. Consistent with the theory, engine tests showed that knock was greatly reduced. Unfortunately, subsequent tests with regular red dyes did not demonstrate any knock inhibition effect, disproving the theory. However, the fact that powerful antiknock additives were found to exist was a major serendipitous discovery.

In the search for more practical additives, it was found that aromatic amines were effective knock suppressors, and in 1920 an experimental car was driven on gasoline with toluidine that had a compression ratio of 7:1. The fuel consumption was improved by 40% over the 4:1 engine. It is also interesting to note that the improved fuel efficiency with the use of the higher compression ratios via antiknock agents also made possible the first non-stop transcontinental airplane flight from New York City to San Diego in the early 1920s.

The unpleasant exhaust odors of the anilines motivated exploration of additive compounds based on selenium and tellurium, but they were also plagued by odors[3]. Eventually, it was found that lead compounds were more acceptable. Accordingly, much research was devoted to discovering and making practical a lead-based additive, tetraethyl lead (TEL). However, TEL was found to promote solid deposits, which damaged exhaust valves and spark plugs. Research showed that scavenger additives made from compounds of bromine and chlorine corrected the problem[4]. National security concerns also played a major role in engine research in the 1930s through the desire to increase the power output of aviation engines in World War II. A heptane known as triptane (2,2,3-trimethyl butane) was discovered with superior knock resistance with TEL, and allowed operation with compression ratios as high as 16:1.

It is interesting to note that lead poisoning was also a concern in those early days, and in 1926 an investigation was commissioned by the US Surgeon General, which determined that, with the proper safeguards, TEL poses no health hazards. Later, in 1950, Dr. Arie Haagen-Smit identified the causes of smog in Los Angeles to be due to the interaction of hydrocarbons (cars being the largest source) and oxides of nitrogen, and in the same year, Eugene Houdry, announced the development of a catalytic converter for auto exhaust. However, lead was found to poison catalytic converters, and 20 years later the US EPA announced that all gasoline stations would be required to carry "unleaded" gasoline, based on ample accumulated evidence that confirmed the negative effects of lead on human health. Although leaded gasoline continued to be tolerated for use in certain applications (e.g., aircraft), it was permanently banned in the US in 1996, in Europe since 2000[5].

The history of the development of today's diesel engine technology also reveals the importance of matching the engine with its fuel, its compression ratio, and controlling the air–fuel mixture preparation (Heywood, 1988). Turbocharging was proposed as long ago as 1925 to increase the amount of air inducted into the engine to increase its power, and single- and multi-stage turbocharger and supercharger systems are still being studied. The availability of on-board electronics in recent decades was a major breakthrough that has led to superior control of the combustion process in both SI and compression ignition engines. For example, precise control over the quantity of injected fuel and the timings of multiple injections in each engine cycle is possible with today's electronically controlled common rail fuel injection systems. Exhaust after-treatment technologies have been introduced that address the high NOx and smoke emissions that characterized early diesel engines. In this case, electronic controls also enabled the development of selective catalytic reduction (SCR) systems for NOx control. Today's improved vehicle technologies also include aerodynamic streamlining for reduced drag, which is a major component of the US Department of Energy's ambitious Super Truck program (Energy.gov, 2014). Further efficiency improvements have resulted from reduced rolling resistance with high-efficiency tires, the installation of equipment that limits idle time, and the use of advanced materials that allow vehicle weight reduction while maintaining safety.

The early pioneering studies revealed much that we now take for granted. This includes important findings such as that engine flame temperatures are higher than the melting point of iron (the cyclic nature of IC engine combustion allows containment of hot gases), that SI engine flame speeds increase in proportion to engine rpm (making it possible to run over wide speed ranges), that formaldehyde is a precursor to ignition that appears in compressed fuel–air mixtures, and that the frequencies of the pressure waves in the combustion chamber during knock vary with the chamber's dimensions and the gas temperature (i.e., knock-induced pressure waves travel at the speed of sound).

[2] Dayton Electric Light Co. (DELCO) president Charles F. Kettering and researcher Thomas A. Midgley began working on the problem of engine knock in electric generator engines. DELCO was acquired by General Motors in 1919 and Kettering was made vice president for research.

[3] Boyd reports that Harry Horning (then General Manager, Waukesha Motor, Co.) visited the GM labs during tellurium additive testing and wrote to Midgley ". . . I reached home safely and everyone is greeting me with gas masks on."

[4] A major initiative was instituted by the Ethyl Corporation working with DuPont for bromine extraction from sea water (10 tons of sea water are needed to provide 1 lb of bromine!)

[5] The use of lead in automotive fuels has been called "The mistake of the twentieth century" (Sourcewatch, 2014).

Opportunities and Challenges

The above brief expedition through some of the history of engine research over the past century reminds us that today's engines and their fuels would not have been developed without close collaboration between engine manufacturers and oil companies. Engines are designed to use fuels with specific ignitability (i.e., octane and cetane numbers). It is also important to note that World Wars and national security also played a major role in defining the automotive fuels now produced at oil refineries. Driven by emissions regulations, more recent fuel formulation changes include addition of oxygenates and the production of fuels with reduced sulfur content to prevent catalyst poisoning. In addition, diesel SCR systems have required installation of an infrastructure to supply urea or Diesel Exhaust Fluid.

One consequence of the collaboration between "big" engine and "big" oil is that transformative changes in transportation systems will not occur easily, unless they are compatible with the existing massive infrastructure. A new concept engine should be able to use available fuels, and a new fuel must run in existing engines (e.g., think ethanol or biodiesel). This can create obstacles for the development of new technologies. For example, it took more than 20 years for the 3-way catalytic converter to be adopted by the automotive industry. Consumer acceptance also plays a role, as seen by the fact that it has taken decades for hybrid electric vehicles to reach any significant market penetration, even though they do not require engine or fuel design changes. Current industry developments, such as the development of down-sized engines, or the use of increased fuel injection pressures, must work harmoniously with existing fuels.

In spite of over a century of research on IC engines, many of the phenomena uncovered in the early works are still unexplained. For example, there is still no satisfactory explanation for the fact that flame speeds in SI engines scale with engine rpm (Reitz, 2013). Practical limits on engine efficiency are still undefined, and are the subject of much current research [e.g., Splitter et al. (2013)]. However, with today's advances in laser diagnostics and computer power, we are in a unique position to optimize engine fuel injection and combustion strategies, as well as fuel composition, to achieve breakthroughs in efficiency and clean combustion. Boyd's (1950) paper addressed future research priorities, many of which are still research topics today. Even then it was realized that understanding and controlling the combustion process and its impact on fuel efficiency has huge economic and petroleum-resource-conservation implications. The use of alternative fuels, such as renewable bio-, or natural gas- and coal-derived fuels, is a path to reduce the reliance on fossil oil. And exploration of new more efficient and clean engine concepts, including their implementation in hybrid, more aerodynamic vehicles with reduced-friction drivetrains, is even more urgently needed today than in the early days of transportation research.

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