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Development of fuel metering techniques for spark ignition engines

P.X. Pham [a,*], D.Q. Vo [b], R.N. Jazar [b]

[a] School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW, Australia
[b] School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne, VIC, Australia

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ABSTRACT

This chapter starts by providing an overview of fuel-metering techniques developed for spark ignition (SI) engines, following by a case study on liquid versus gaseous phase liquified petroleum gas (LPG) port injection in a single-cylinder SI engine. Fuel-metering approaches, from the least to the most modern, include carburettor, throttle body injection (TBI), manifold port injection (MPI or sometime called PFI, port fuel injection), and gasoline direct injection (GDI). Based on the mixture formation process, GDI engines can be categorised into air-guided, wall-guided, and spray-guided methods while based on the ignition modes they can be homogeneous spark ignition - (HCI), stratified spark ignition (SPI) and homogeneous charge compression ignition (HCCI) engines. The comparative study shows significant variations in cylinder to cylinder mixture distribution for both liquid and gaseous LPG phases. The experimental data confirms the power and efficiency advantages of liquid phase injection over gaseous phase injection. Analysis shows the charge state at the end of compression is the major contributor to the performance difference. Secondary differences such as the mixture homogeneity also have an important impact. The lower temperature combustion with liquid phase LPG also delivers substantial NOx emission reduction. Suggestions are made for overcoming the deficiency of gaseous phase injection which may be preferred as its application avoids the high cost of the high pressure in-tank LPG pump needed for liquid phase injection.

1. Introduction

It is estimated that almost 6 billion automobiles are operating worldwide today and an increase of 35% is expected by 2020 [1]. The rapid increase is one of the biggest contributors to the energy crises as the production of crude-oil may not be able to fulfill the energy demand. Fig. 1 shows the dependence of total world oil demand from the transport sector in Mega Tonne of Oil Equivalence (MTOE) during the period from 1971 to 2030 [2]. The increase in total energy demand observed in Fig. 1 is mainly due to the activities of transport sector. The amount of energy needed for other sectors, rather than transportation, has fluctuated around 1,000 MTOE throughout this period. Energy that is consumed for transport, however, has increased by 200 MTOE approximately every five years and is expected to increase by nearly 60% during the period from 2015 to 2030. In 2015, the transport sector demand (2,000 MTOE) was almost three times that of 1971 (700 MTOE). From this review, one gets the impression that the term energy crises should be replaced by automotive energy crises.

Options for automotive fuels have traditionally been hydrocarbons based, namely gasoline and diesel produced from crude-oil resources. The fossil sources which account for more than 97% of global transport fuel used [3] have been known for some time that will soon be depleted. The BP statistical review of world energy in 2016 [4] estimated that the life of the sources was approximately 50 years based on the ratio of total world oil reserves to average yearly oil production (R/P). The R/P ratio and number of reserved barrels estimated for different continents along with their proportion of sharing the total energy from 1995 to 2015 are shown in Table 1. From Table 1 one can see that Asia Pacific has an R/P only 14 and share only 2.5% of the total world energy reserves. Witnessing the economic booms and population growth in that continent particularly in China and India, utilization of alternative energy sources are in urgent need to ensure a sustainable development for the continent.

In terms of crude-oil prices, the world has experienced two oil crises (1861–1869, 1973–1974 and 1978–1980) [5,6] and this has not been included the skyrocketing price of crude-oil witnessed recently from 2009–2014 [4]. The first oil crisis, which

* Corresponding author.
E-mail addresses: x.pham@sydney.edu.au (P.X. Pham), dai.voquoc@rmit.edu.au (D.Q. Vo), reza.jazar@rmit.edu.au (R.N. Jazar).

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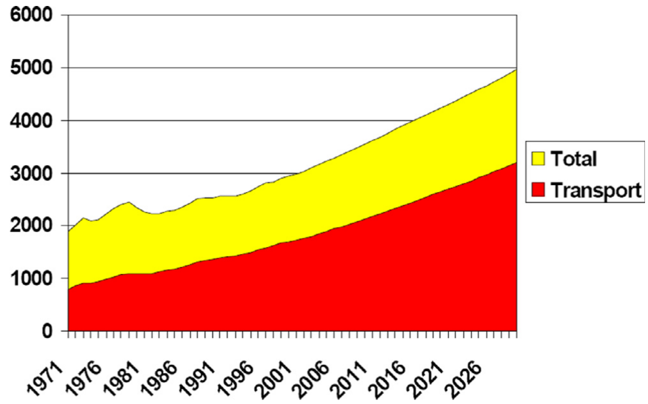

Fig. 1. Transport and total world oil demand in MTOE [2].

occurred in 1973–1974, had the deepest impact on the world's economic system as the crude-oil price increased 4 times from US$3 to US$12 per barrel. During the second oil crisis, which started in 1978, crude-oil price soared to US$25 per barrel in 1979 and then hit US$38 per barrel two years later. In 2005, the peak price of crude-oil was near US$70 per barrel, up from US$56 in 2004. A record price of US$120 per barrel was reached in April 2014. This increasing trend of crude-oil price could be named as the third oil crisis.

Automotive exhaust emissions have detrimental effects on human beings as well as ecology. The tail-pipe emissions are composed of many pollutants, mainly regulated components (NOx, CO, CO_2, HC and particulate matter - PM) but also may include non-regulated components (CH_4, SOx and Pb). Air pollutants have short-term and long-term effects on human health. The short-term effects of pollutants may result in serious injury or even death due to inhalation. Examples of this include the deaths due to air pollution of sixty-three people in December 1930 in Meuse Valley - Belgium, twenty people in a four-day period in 1948 in Donora [7], and the deaths of eighty people during four days in New York City in 1970 [7,8]. Although the short-term effects of emissions are rarely encountered in large populations, the mentioned events are enough to warn people, including automotive engineers, to manage automotive exhaust emissions. In the long-term, however, polluted air may affect human beings gradually over a period of several years or even decades. Hence, the symptoms of diseases resulting from the polluted environment are very hard to diagnose. Identified adverse health affects associated with automobile exhaust emissions include impacts on [8]:

- Eyes (irritation)
- Skin
- Nervous system
- Respiratory system (lung asthma, bronchitis, alveolitis, and lung cancer)
- Cardiovascular system
- Gastrointestinal system
- Reproductive system

One measurable impact of pollution is the billions of dollars paid annually to treat patients affected by exhaust emissions. For instance, it was estimated that Australian capital cities had to pay between AU$3–7 million in 2003 for the hospital and mortality costs due to transport fuel emissions. The above mentioned figures do not include private doctors, pharmaceutical costs of day-to-day treatment, or productivity impacts [9]. In addition, automotive pollution impacts global warming and acid rain production. Global warming is due to the enhanced greenhouse gas effect caused by the addition of water vapour, CO_2 (the main contributor with 55% of the global warming effect), and other greenhouse gases (such as CFCs, HFCs, HCFCs, CH_4, and N_2O), to the atmosphere, which results in the retention of infrared radiation [7]. The transport sector contributes up to 69% of the total of CO_2 emissions [10]. As an example, global warming leads to ice melting in the North Pole and therefore an increase in the sea level. Acid rain results from chemical reactions between NOx and SOx pollutants and H_2O in the atmosphere to acids such as H_2NO_3, H_2NO, H_2SO_4, and H_2SO_3. Acid rain can destroy crops, fish, and other aquatic life.

As a countermeasure, industrial countries have enforced increasingly stringent emission standards for automobiles with different types of fuels. The United States was the pioneer in the field and automotive exhaust emissions were first limited by law in 1961. Japan came second five years later and European countries began discussing policies to reduce automotive exhaust emissions in 1970, leading to the introduction of the ECP2–15 series of standards in 1972. A new series of European Standards (known as Euro 0), were introduced in 1987 [11,12] followed by the Euro I to Euro VI Standards, which were introduced between 1991 and 2014 [12–14]. It is notable that Euro V and VI (came into effect in 2008 and 2014, respectively) have first time introduced particle number for diesel engines, similarly, Euro VI has enforced particle number regulations for petrol engines [13,14]. Nowadays, Euro Standards, as a

Table 1
World total fossil-oil proven reserves: 2016 perspective [4].

	Thousand million barrels (End 1995)	Thousand million barrels (End 2005)	Thousand million barrels (End 2014)	Thousand million barrels (End 2015)	Thousand million tonnes (End 2015)	Share of total [%] (End 2015)	R/P ratio (End 2015)
North America	126.9	223.6	238	238	35.9	14	33.1
S.&Cent. America	83.7	103.6	331.7	329.2	51	19.4	117
Europe & Eurasia	141.2	139.5	154.6	155.2	21	9.1	24.4
Middle East	663.3	755.5	803.8	803.5	108.7	47.3	73.1
Africa	72	111.3	129.3	129.1	17.1	7.6	42.2
Asia Pacific	39.1	40.8	42.6	42.6	5.7	2.5	14
Total World	1126.2	1374.4	1700	1697.6	239.4	100%	50.7
Of which:							
1. OECD	149.2	244.0	253.9	255.3	38.0	15	29.7
2. Non-OECD	976.9	1130.4	1446.1	1442.3	201.3	85	58
3. OPEC	786.6	927.8	1211.1	1211.6	169.9	71.4	86.8
4. Non-OPEC	339.6	446.6	488.9	486	69.4	28.6	24.9
5. European Union	8.3	7	5.6	5.6	0.7	0.3	10.1
6. CIS	121.5	122.2	141.9	141.1	19.1	8.3	27.8