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Review

Natural-gas fueled spark-ignition (SI) and compression-ignition (CI) engine performance and emissions

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ABSTRACT

Natural gas is a fossil fuel that has been used and investigated extensively for use in spark-ignition (SI) and compression-ignition (CI) engines. Compared with conventional gasoline engines, SI engines using natural gas can run at higher compression ratios, thus producing higher thermal efficiencies but also increased nitrogen oxide (NO_x) emissions, while producing lower emissions of carbon dioxide (CO_2), unburned hydrocarbons (HC) and carbon monoxide (CO). These engines also produce relatively less power than gasoline-fueled engines because of the convergence of one or more of three factors: a reduction in volumetric efficiency due to natural-gas injection in the intake manifold; the lower stoichiometric fuel/air ratio of natural gas compared to gasoline; and the lower equivalence ratio at which these engines may be run in order to reduce NO_x emissions. High NO_x emissions, especially at high loads, reduce with exhaust gas recirculation (EGR). However, EGR rates above a maximum value result in misfire and erratic engine operation. Hydrogen gas addition increases this EGR threshold significantly. In addition, hydrogen increases the flame speed of the natural gas–hydrogen mixture. Power levels can be increased with supercharging or turbocharging and intercooling. Natural gas is used to power CI engines via the dual-fuel mode, where a high-cetane fuel is injected along with the natural gas in order to provide a source of ignition for the charge. Thermal efficiency levels compared with normal diesel-fueled CI-engine operation are generally maintained with dual-fuel operation, and smoke levels are reduced significantly. At the same time, lower NO_x and CO_2 emissions, as well as higher HC and CO emissions compared with normal CI-engine operation at low and intermediate loads are recorded. These trends are caused by the low charge temperature and increased ignition delay, resulting in low combustion temperatures. Another factor is insufficient penetration and distribution of the pilot fuel in the charge, resulting in a lack of ignition centers. EGR admission at low and intermediate loads increases combustion temperatures, lowering unburned HC and CO emissions. Larger pilot fuel quantities at these load levels and hydrogen gas addition can also help increase combustion efficiency. Power output is lower at certain conditions than diesel-fueled engines, for reasons similar to those affecting power output of SI engines. In both cases the power output can be maintained with direct injection. Overall, natural gas can be used in both engine types; however further refinement and optimization of engines and fuel-injection systems is needed.

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1. Document layout

A detailed review of previous work investigating natural gas as a fuel in reciprocating piston engines, both spark-ignited (SI) and compression-ignited (CI), is presented. Previous reviews (such as reference [1]) only discussed SI engines, while this paper includes CI engines in dual-fueling. In addition, in reference [1] there is little discussion of exhaust emissions, while it is very specific about other topics, such as lean burn, spark timings and intake flow passages. We first discuss the need for alternative fuels in terms of the current state of fossil fuel reserves, as well as issues regarding pollution. General performance parameters used in engine testing and analysis are then introduced in order to guide the discussion in later sections. How natural gas is implemented in SI and CI engines is then discussed. Engine performance, combustion characteristics, and emission levels are assessed and quantified. Natural gas is the main fuel discussed in this work; other fuels (such as hydrogen addition, high-cetane pilot fuels etc) serve as secondary fuels to facilitate or improve natural gas engine operation, and have been presented as such throughout the manuscript. Multi-fuel operation can be considered in both SI and CI engines. The term dual-fuel is used in the CI section exclusively, to indicate when a second fuel, such as diesel, is injected in the cylinder in order to act as a source of ignition of the natural gas in CI engines. Finally, the overall conclusions and recommendations are presented.

2. Introduction

2.1. Natural gas and biogas as part of the general fuel supply

Fossil fuel consumption is steadily rising as a result of population growth in addition to improvements in the standard of living. It can be seen from Fig. 1 that world population has been increasing steadily over the last 5 decades, and this trend is expected to continue [2]. As a result, total energy consumption has grown by about 36% over the last 15 years [3]. Energy consumption is expected to increase further in the future, as world population is expected to grow by 2 billion people in the next 30 years [2]. These energy trends can be seen in Fig. 2. Increased energy demand requires increased fuel production, draining current fossil fuel reserve levels at a faster rate. In addition, about 60% of the world's current oil reserves are in regions that are in frequent political turmoil [3]. This has resulted in fluctuating oil prices and supply disruptions. For example, Fig. 3 shows that oil prices doubled from June 2007 to May 2008, only to halve in May 2009 [4].

Crude oil is a finite resource dependent on availability and stability of fossil fuel supplies. As internal combustion (IC) engines are expected to continue service well into the next century, the road transport sector in particular needs more secure and sustainable future fuel sources. Legislated reductions of certain exhaust gas emissions are another issue facing the current generation of IC engines. For example, the EURO 5 emission regulation that came into force in September 2009 [5] requires both gasoline and diesel engines to reduce their emissions of nitrogen oxides (NO_x) by about 30%. At the same time, consumers expect improved engine performance and fuel consumption. This is reflected in the literature, where there is an increasing need to extract more power from smaller powerplants (increasing power output per unit engine mass; otherwise known as specific power) [6–12]. In order to accomplish these goals, a new generation of energy-conversion powerplants would need to be produced. This new generation would have improved thermal efficiency, increased specific power, and reduced harmful exhaust emissions [6,9,13]. Various options to increase efficiency and power while reducing emissions of automotive powerplants already exist, such as hybrid systems and high-pressure direct fuel injection. While these innovations have worked very well in approaching these targets, alternative fuels will need to be implemented in order to surpass them as well as reduce crude oil dependence on a larger, more significant scale.

Table 1
Typical natural gas composition by volume (from [14]).

Species	Content
Methane	92%
Ethane	3%
Propane	0.7%
Butane	0.02%
Pentane	0.1%
Carbon Dioxide	0.6%
Nitrogen	3%

One of the more established alternative fuels is natural gas. Natural gas is a gaseous fossil fuel, consisting of various gas species. A detailed typical composition is shown in Table 1 [14]. Fossil natural gas is found either together with other fossil fuels (such as crude oil in oil fields, as well as with coal in coal beds) or on its own. The properties of natural gas are very similar to those of methane, which is its primary constituent. One of the reasons why natural gas is the focus of this work is its significantly larger proven reserves compared with crude oil (the current known reserves-to-production (R/P) ratio for crude oil is about 40 years, while for natural gas it is about 60 years) [3]. The variation of these R/P ratios over the past quarter century is also shown in Fig. 4. The R/P levels of crude oil and natural gas have been relatively steady over the last two decades. This is because, in addition to new reserves being discovered, previous supplies of natural gas that were previously inaccessible can now be obtained as a result of new technology allowing practical and economical recovery.

It will be seen in the following that SI and CI natural-gas fueled engines would provide better performance with direct injection of the gas in the engine cylinder. This requires gas pressures up to 30 MPa. Compressing gas directly from atmospheric pressure and temperature to 30 MPa in isentropic compressors requires work input equal to about 3.6% of the energy content (enthalpy of combustion) of the natural gas, and more in terms of exergy content.