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Short communication

Numerical study of the substitutional diesel fuel energy in a dual fuel diesel-LPG engine with two direct injectors per cylinder

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ABSTRACT

The paper proposes a numerical study of the operation of a dual fuel diesel-Liquefied Petroleum Gas (LPG) engine featuring direct injection (DI) of both the diesel and the LPG with two separate injectors per cylinder. Aim of the study is the determination of the pilot/pre diesel fuel energy needed to operate the engine diesel-like in terms of combustion with a main injection of LPG. Computational results are proposed over the full range of speeds and loads for a 1.6 l high speed direct injection (HSDI) diesel engine. The engine is modified to accept the direct injection of the LPG fuel through the adoption of a second direct injector per cylinder. Only the opportunity of injecting the main LPG after the pilot/pre diesel injections is considered in the study. However, more complex strategies are certainly possible. The results demonstrate the opportunity to achieve diesel-like fuel conversion efficiency and torque and power outputs while replacing the most part of the diesel energy – up to 95% at medium – high loads - with the more environmentally friendly LPG. This replacement reduces the pollutants' emissions and improves the energy mix of transportation fuels.

1. Introduction

Liquefied Petroleum Gas (LPG) is an alternative transportation fuel widely researched, having substantial reserves, as it is produced from Natural Gas (NG) processing and crude oil refining. It is a much simpler hydrocarbon much easier to vaporize, mix and burn than gasoline and diesel. Many alternatives are being sought to develop single fuel or dual fuel LPG engines of the spark ignition (SI) or compression ignition (CI) type. The port fuel (PFI) injection (and sometimes the manifold injection) of LPG in a SI engine set-up is obviously the most popular configuration considered. The direct injection (DI) of LPG in a SI engine set-up is also relatively popular, as well as popular is the PFI of LPG in a CI engine with diesel injection ignition.

Reference [1] studies the lean operation of a LPG DI SI engine featuring a spray-guided combustion system. Under light loads, the lean operation improves the fuel economy up to 18%. FTP-75 cycle simulation shows fuel economy improvement by 6%.

Reference [2] proposes other experiments on the same engine. The engine was operated at a constant speed of 2000 rpm under 0.2 MPa brake mean effective pressure (BMEP). For combustion stability with the stratified LPG mixture, an inter-injection spark ignition (ISI) strategy is employed. This is an alternative control strategy with a two-stage injection. The effects of the compression ratio on the fuel economy are assessed. The fuel consumption did not reduce when the compression ratio was increased.

Same engine set-up is also used in reference [3]. The lean stratified combustion of LPG is investigated at five representative engine operating points. The spray-guided combustion system design improves fuel economy due to the increased flame speed. However, significant amounts of NO_x are produced due to local rich region. Excessively lean mixture formed around the periphery of the fuel spray increase the HC emissions.

Also reference [4] uses this engine. This time, the study is addressing the issue of relatively high levels of particulate matter (PM) emitted by gasoline direct injection engines. Running stoichiometric, particulate matter emissions of a LPG direct injection engine were substantially lower than those from a gasoline direct injection engine.

A PFI gasoline engine modified for LPG is proposed in Reference [5]. The authors study the influence of ignition timing on performances and knock sensitivity different λ (ratio of the actual to stoichiometric air/fuel ratio (AFR)) at wide open throttle and engine speed of 4300 rpm. Highest brake power and highest efficiencies are obtained with a tuned ignition timing at $\lambda = 1$. The lowest exhaust emissions are obtained at $\lambda = 1.3$. Advancing the ignition timings increases the HC and NO_x emissions, while the effect on CO emissions is negligible.

A PFI gasoline engine modified for LPG is also studied in Reference [6]. Lower CO and HC emissions are obtained with LPG compared to gasoline while the NO_x emissions increase with LPG. Engine performance values with LPG are close to gasoline.

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Reference [7] studies PFI injection systems of gasoline and LPG detailing the fuel injectors flow characteristics. The study provides guidelines to tune the injection timing when replacing gasoline with LPG as the fuel.

A single cylinder diesel engine is modified to operate as SI with a compression ratio of 10:1 in reference [8]. Operation at 1500 rpm with lean combustion of LPG is considered to optimize the piston squish area. A 30% squish area piston results in improved performance at all operating conditions. Piston squish area beyond 30% causes instability in combustion towards lean limit. Lower HC emissions are obtained with 25% and 30% squish area pistons. NO emission increased with 25% and 30% compared to 35% and 40% squish area pistons.

Regarding the dual fuel diesel LPG CI engines, a recent review is proposed in reference [9]. The review only considers the option of PFI or manifold injection of LPG in an otherwise conventional direct injection diesel engine. The article reviews about the work done to improve performance, combustion and emission parameters of the specific design. The use of LPG in diesel engines reduces the PM and NO_x emissions but at same time penalizes the part load efficiency. Power output also deteriorates vs. the diesel only operation.

Reference [10] considers upstream injection of LPG, with direct injection of DME-diesel. The addition of LPG delays combustion phase of DME-diesel, with peak cylinder pressure and temperature declining, NO_x emission reducing and particle number concentration increasing first, then decreases by increasing the LPG fuel energy.

Dual fuel LPG diesel combustion is also studied in Reference [11]. At low engine loads, the peak cylinder pressure, pressure rise rate, and heat release rate decrease by increasing the LPG energy. At high engine loads, these parameters are maximum with LPG energy 25%. In this work, the ignition delay period and the combustion duration increase with the increase of LPG at low engine loads. However, they firstly increase and then decrease at high engine loads. At each engine load, there is an optimal LPG energy. The efficiency of the dual fuel operation is lower than that of diesel only at low engine loads. It is however and higher at high engine loads. By increasing the LPG energy, HC and CO emissions increase, while smoke emission decrease and NO_x emissions are also lower [11].

The SI engine single fuel option thus permits gasoline-like torque and power outputs as well as full load and part load efficiencies, DI having advantages vs. PFI for what concerns part load fuel conversion efficiency. The CI engine dual fuel option with upstream injection of the LPG and direct injection of the diesel provides in principle some advantages vs. the SI for what concerns the fuel conversion efficiency especially at part load. However, in practice the upstream injection of the LPG strongly limits the opportunities to achieve diesel-like efficiencies over the full speed and load map. A solution to achieve diesel-like torque and power outputs and fuel efficiencies over the full range of speeds and loads was already proposed in [12–17]. It requires to inject the LPG directly in the combustion chamber with a second direct injector. The rationale behind this solution is presented in the next section.

2. Dual fuel direct injection

The idea of directly injecting diesel and NG (or better LNG, Liquified Natural Gas) is >3 decades old, as it was proposed by Professor Hill of the University of British Columbia (UBC) many years ago [22], and then adopted by Westport to modify a large number of Heavy Duty Diesel (HDT) Trucks to run with the alternative fuel and a minimal part of diesel (HPDI) [23]. In the early 1980's, Professor Hill aimed at NG as a fuel in diesel engines to reduce emissions of nitrogen oxides (NO_x) and particulate matter (PM) while preserving performance, fuel economy, durability, and reliability of the diesel engine. However, Professor Hill and Westport adopted a single injector for both the diesel and the alternative fuel. This limited the opportunities to develop more complex mixing and combustion strategies, but it made the conversion simple.

The use of two different direct injectors, one for the diesel, and one for the LPG, is proposed here. This makes the difference vs. the prior state-of-the-art. If the two injectors are operated with pilot diesel and LPG primary, then similar to Westport HPDI performances with pilot diesel and LNG primary should be provided.

Westport HPDI with LNG is very well known to work [22] without any downfall. The Westport single direct injector dual fuel is a consolidated technology that does not need to be proved effective here, as in addition to dynamometer experiments, a large fleet of modified trucks of thousand units is on the road. The system uses pilot diesel and main LNG injections. It delivers same of diesel full load power and torque curves - a major requirement of the engine conversion to minimize the impacts on the vehicle control unit. The 15 l Westport ISX 450 diesel + LNG - Fig. 1 - has exactly same torque and power of the original Cummins ISX 450 [22], with actually slightly better torque/power outputs at 1900 and 2000 rpm, as well as 1600 rpm [22].

Westport HPDI uses a small amount of diesel as a pilot ignition source, or "liquid spark plug" in Westport terms. This is realised with a single injector featuring a dual-concentric needle design and the

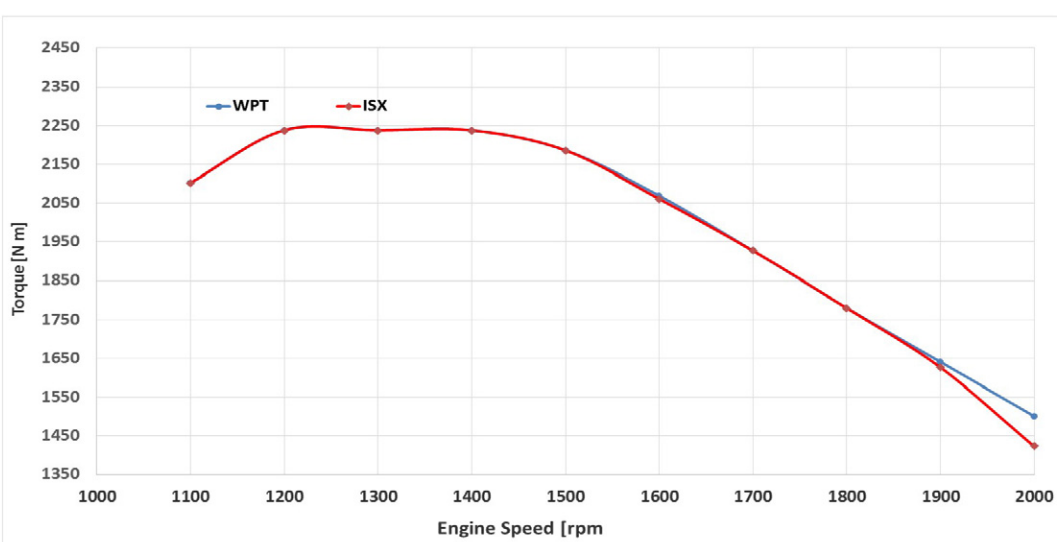

Fig. 1. Torque curves of the 15 l Westport ISX 450 diesel + LNG (WPT) and Cummins ISX 450 (ISX). Data from [22]. The converted WPT engine has exactly same torque and power of the original ISX engine, with actually improved top speed output.