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Research article

Analysis of the effects of diesel/methane dual fuel combustion on nitrogen oxides and particle formation through optical investigation in a real engine

Silvana Di Iorio, Agnese Magno *, Ezio Mancaruso, Bianca Maria Vaglieco

Istituto Motori-CNR, Napoli, Italy

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ABSTRACT

Great attention was paid to nitrogen oxides and particulate matter emitted by the compression ignition engines. The adoption of methane dual fuelled with diesel could contribute to the reduction of these pollutants.

This paper aims to investigate the combustion phenomena occurring when a premixed methane/air charge is ignited by the direct injection of diesel fuel. The research activity was performed on a production compression ignition engine, three-cylinder, 1.0 L, equipped with a common rail injection system. In order to operate in diesel/methane dual fuel mode, the intake manifold of the engine was modified to set an electronic port fuel injector suitable for gaseous fuels. Different engine speeds and loads were tested. For each engine condition, a small part of the total energy was provided by the direct injected diesel fuel while the remaining by the methane. Thermodynamics analysis of the combustion process was performed through conventional measurement involving in-cylinder pressure acquisition. Endoscope based optical techniques were carried out for the combustion visualization with high spatial distribution and temporal evolution. Two-colour pyrometry method was applied to the flame images to evaluate the temperature and the soot concentration. This method allows to achieve a better insight about the pollutant formation. Experimental results revealed that DF combustion occurs with lower temperature and soot formation than diesel operation thus leading to lower nitrogen oxides and particle emissions at exhaust.

1. Introduction

In the past decade, advances in exploration and production technologies have considerably increased recoverable supplies of methane making it an attractive alternative fuel for internal combustion engines in a wide range of applications, from stationary power production to road and marine transportation [1]. Methane is the simplest hydrocarbon; it has no carbon-carbon bonds and it has high hydrogen to carbon ratio resulting in clean burning qualities [2]. Therefore, the use of methane as supplement to diesel fuel in compression ignition (CI) engines has achieved particular attention thanks to its potential to reduce pollutant emissions from vehicles operating in the congested urban area of some countries [3]. It is expected that by 2020, the methane share in the bulk of motor fuels will reach 11% in Asia, 12% in Americas and 14% in Europe and the world gas consumption in transport is expected to increase from 20 bcm in 2010 up to 40–45 bcm in 2030 [4].

The most suitable way to utilize methane in CI engines without significant technological modifications is the dual fuel (DF) concept. The poor ignition characteristics of the low cetane number (CN) gas fuel prevents ignition at the temperature reached under compression in a CI engine. In order to ensure ignition and sustain combustion of the premixed methane/air charge, an appropriate amount of high CN liquid fuel is injected in the cylinder [5].

DF combustion allows to reduce the main CI engine pollutants that are nitrogen oxides (NO_x) and particulate matter (PM) [6]. Moreover, carbon dioxide (CO_2) emissions are lower in DF mode with respect to conventional diesel operation [7]. Emissions of carbon monoxide (CO) and total hydrocarbon (THC) are increased when the engine runs in DF mode due to the lower thermal efficiency [8]. Concerning THC emissions from DF combustion, they consist mainly of methane hydrocarbons (MHC) that have negligible reactivity in the photochemical smog cycle but, on the other hand, their global warming effect is 30 times the one of CO_2 [3]. In order to overcome the drawback of high CO and THC emissions from DF combustion, some alternative strategies were proposed such as air inlet preheating combined with the use of exhaust gas recirculation (EGR) [9], intake air throttling [10], advanced diesel pilot injection [11] and the use of biodiesel as ignition source instead of diesel fuel [12]. Overall, several studies have investigated the effect of methane addition to diesel fuel on pollutant emissions [13–17]. Nevertheless, few studies deal with the particle size characterization from DF combustion systems [18–20]. Hernandez et al. [18] analysed the

* Corresponding author at: Istituto Motori-CNR, Via G. Marconi 4, 80125 Napoli, Italy.
E-mail address: a.magno@im.cnr.it (A. Magno).

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separate effect of hydrogen, methane and carbon monoxide addition on the performance, combustion efficiency and pollutant emissions of a supercharged 2 L diesel engine. Concerning the methane/diesel operation, they observed that the particle number concentration decreases as the diesel fuel replacement increases while the particle mean diameter does not change. Yang et al. [19] studied the particle emissions of diesel/natural gas dual-fuel operation on a turbocharged four-cylinder common rail (CR) engine with varying pilot injection timing. They found out that from the view of reduction particle emissions, the range of optimal pilot injection timing is from 17 crank angle degrees (cad) after top dead center (ATDC) to 20 cad ATDC and thus it is not reasonable to advance excessively the pilot injection timing. From experience of authors [20] that analysed the particles emitted by a small CI engine modified to run in diesel/methane mode, at different operating conditions, DF combustion allows to reduce the total particle number with respect to diesel operation. On the other hand, the particle diameter depends on the combustion evolution due to the interaction between diesel fuel and methane.

The topic of particle number and size is particularly relevant and because of the negative impact of ultrafine particles on environment and human health, it requires intensive researches [21]. Great efforts were paid to reduce the particles emissions from internal combustion engines also because of the new emission legislations that include restrictions on the particle number beyond the particle mass [22].

On the other hand, experimental investigations involving optical visualization of in-cylinder phenomena could contribute to achieve a better understanding of the effect of DF strategies on combustion characteristics and pollutant formation mechanisms. Optically accessible engines, realized by replacing a part of metallic cylinder by quartz or sapphire windows, allow a good visualization of injection and combustion events [23,24]. Taniguchi et al. [25] analysed DF combustion at different operating conditions by carrying out optical measurements on a research engine. They observed that at low loads, the gas fuel far from the diesel spray did not reach the flammability limits. As consequence, methane was emitted at exhaust as unburned MHC. Dronniou et al. [26] performed simultaneous measurements of natural luminosity, OH chemiluminescence and 2D PLIF imaging on a light duty single cylinder research engine running in DF mode. They provided some fundamental combustion mechanisms that occur when a premixed mixture is ignited by a pilot injection of reactive fuel. They observed that, independently from the equivalence ratio, the ignition occurred in the region near the bowl wall. However, they concluded that additional works are necessary to evaluate the advantages of DF strategies. Optical investigation of DF combustion was performed also by the authors [27] on a transparent engine equipped with the head of a CR, 2 L production engine. They found out that the combustion starts under the nozzle tip and then the flames move towards the bowl wall.

It is worth underlining that transparent engines require geometrical modifications of combustion chamber thus modifying the flow characteristics. Moreover, limited strength of transparent window entails speed and load limitations [28]. On the contrary, endoscope based optical techniques can be applied to production engines with the aim to observe combustion evolution in real engine geometries and in wide range of operating conditions [29–31].

The objective of this paper is to investigate the cause-effect relationship between combustion evolution and pollutants formation of diesel/methane DF operation. The research was carried out on a production CI engine modified to run in DF mode: a gas injector was installed in the intake manifold and it was managed by a delay unit developed in Istituto Motori. The original electronic control unit (ECU) was retained for diesel injection control. Experiments were performed at different engine speeds and loads. The engine was first operated in conventional mode with neat diesel fuel and then in diesel/methane DF configuration. Under DF mode, at a fixed engine speed, sufficient amount of diesel fuel was injected to cover the 10% of the maximum torque output; the remaining percentage of the desired torque output was achieved by methane. Combustion behaviour of DF combustion was analysed through indicating data. Endoscope based optical techniques were implemented to visualize the combustion event in the chamber. Flame images were post-processed by two-colour pyrometry method to provide qualitative information about the flame temperature and the soot concentration that were correlated to NO_x and PM emissions measured at exhaust, respectively. Moreover, particular attention was paid to the characterization of the particles in term of number and size at the exhaust.

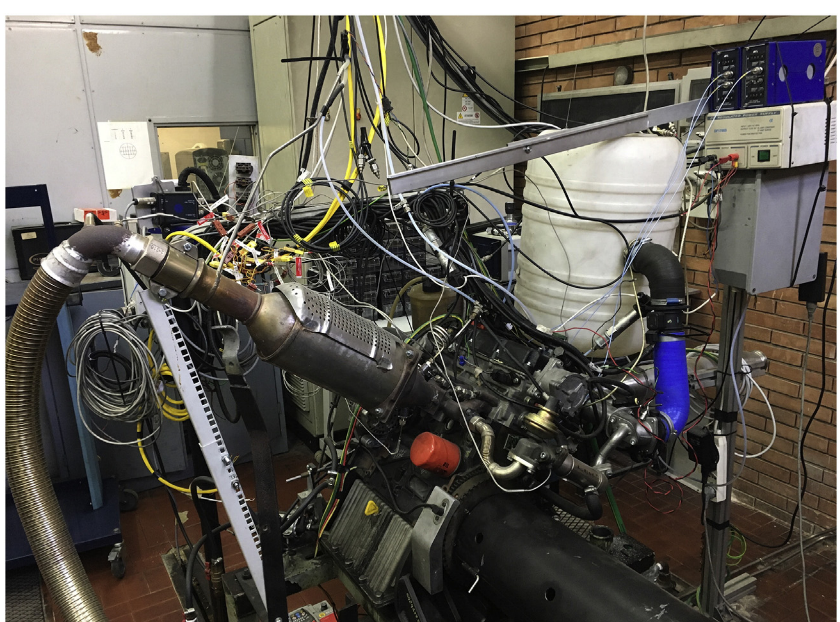

Fig. 1. Test engine.