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Characterization of particle number and mass size distributions from a small compression ignition engine operating in diesel/methane dual fuel mode

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HIGHLIGHTS

- Particle number and mass size distributions were detected at exhaust of CI engine operating in DF mode.
- DF operation reduces the number of particles at all operating conditions.
- The size of particles emitted in DF operation is affected by the different pilot combustion phase.
- In-cylinder indicating data analysis of DF combustion explains different particle number and mass at exhaust.

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ABSTRACT

The use of gas fuels in compression ignition engines through dual fuel technology represents a promising way to reach a good compromise among sustainable development, energy conservation and environmental preservation. Dual fuel is an operation mode in which the gas, the primary fuel, is mixed with air in the intake manifold before entering into the cylinder. The air–fuel mixture is then ignited by a small amount of liquid fuel directly injected in the cylinder towards the end of the compression stroke. Methane is particularly attractive because of its potential to reduce particulate emissions that are likely the most critical issue of diesel engine exhaust. The present work deals with an experimental activity carried out on a compression ignition engine modified to run in diesel/methane dual fuel mode. The engine is a three-cylinder, 1.0 L of displacement, equipped with a common rail injection system. Experiments were carried out at different engine speeds and loads. For each engine speed, a fixed part of the total energy was supplied by the diesel combustion and the remaining by varying the concentration of methane in the intake. Thermodynamics analysis of the combustion process was performed by in-cylinder pressure signal. Particulate matter emissions were measured at the exhaust by commercial instruments. The sizing and the counting of the particles were performed in the diameter range 5.6–560 nm. It was found out that the effect of diesel/methane combustion on particle formation is strongly affected by the operating condition. In particular, it arose that DF combustion emits lower amount of particles whose size with respect to diesel fuel is related to the different combustion evolution.

Abbreviations: AFR_{st}, stoichiometric air fuel ratio; ATDC, after top dead center; BSFC, brake specific fuel consumption; cad, crank angle degree; CH_4, methane; CI, compression ignition; CO, carbon monoxide; CoV, coefficient of variation; CO_2, carbon dioxide; CN, cetane number; CR, common rail; D, diesel; DEED, Dekati Engine Exhaust Diluter; DF, dual fuel; D_m, mean particle diameter; DOC, diesel oxidation catalyst; DOI, duration of injection; D_p, particle diameter; DPF, diesel particulate filter; ECU, electronic control unit; EEPS, Engine Exhaust Particle Sizer; EGR, exhaust gas recirculation; FSN, filter smoke number; imep, indicated mean effective pressure; λ, relative air–fuel ratio; LHV, lower heating value; $\dot{m}$, mass flow rate; M, total particle mass; MHC, methane hydrocarbons; N, total particle number; NO, nitrogen monoxide; NO_x, nitrogen oxides; PES, percentage energy substitution; P_b, brake power output; PM, particulate matter; PMP, particle measurement programme; PMSDF, particle mass size distribution function; PNSDF, particle number size distribution function; ROHR, rate of heat release; ρ, density; SM, smoke meter; SOC, start of combustion; SOI, start of injection; T_b, brake torque output; TDC, top dead center; THC, total hydrocarbons.

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1. Introduction

Compression ignition (CI) engines play an important role in transportation and power generation because of their high efficiency, affordability, and reliability [1]. Nowadays, most of the research on CI engines is focused on the potential of alternative fuels, both liquid and gaseous, to reduce the dependence from diesel fuel [2,3]. The exigency of a viable alternative to fossil fuels is mainly due to the depletion of petroleum reserves and to environmental problems attributable to exhaust emissions. Besides them, other issues such as increasing fuel price, the need of supplying the fuel demand from local sources reducing the import of crude oil have prompted for the fuel diversification [4].

Methane is particularly attractive as alternative fuel for CI engines because of its renewable nature and clean burning qualities [5]. The most suitable way to utilize it without relevant technological modifications is the dual fuel (DF) concept: because of its poor ignition characteristics, methane cannot totally replace diesel but it can be used as supplement to the liquid fuel. In diesel/methane DF operation, in fact, the gas fuel is injected into the intake manifold to mix uniformly with air; the premixed air–methane mixture is drawn into the cylinder and it is ignited by diesel fuel injected directly in the chamber around the top dead center (TDC) [3].

Diesel piloted combustion of methane allows to reduce the pollutants of most concern for a CI engines that are nitrogen oxides (NO_x) and particulate matter (PM) [6]. Moreover, DF operation benefits of lower carbon dioxide (CO_2) with respect to conventional diesel mode [7]. The main limitations of diesel/methane DF combustion are the high carbon monoxide (CO) and total hydrocarbon (THC) emissions, the latter consisting mainly of methane hydrocarbons (MHC) [8]. The use of after-treatment devices such as diesel oxidation catalyst (DOC) could help to overcome the drawbacks of the high CO. On the other hand, typical DOCs are not very effective with MHC abatement since methane is the most stable of the hydrocarbons. Catalysts covered with much higher precious metal loadings, in fact, could be more efficient for breaking down methane molecules [9]. Some solutions have been suggested to limit both CO and THC emissions making DF fuelling more attractive. Papagiannakis [10] proved through experimental and numerical investigations that air inlet preheating combined to exhaust gas recirculation (EGR) can reduce CO without compromising significantly nitrogen monoxide (NO) emissions. Abedelaal et al. [11] showed that EGR contributes to reduce THC emissions by enriching the air-fuel mixture. Advanced diesel pilot injection was proposed by Yang et al. [12] to reduce the high CO and THC emissions. Biodiesel was used as pilot fuel instead of diesel contributing to a reduction of CO, THC and PM with a small penalty in NO_x emissions [13–15].

Overall, several experimental and theoretical studies have presented performance and emission characteristics of CI engines operating in DF mode at different load settings and engine rotational speed combinations [16–19]. Optical diagnostics have been also applied to have a better understanding of DF combustion behavior and pollutant formation mechanisms [20–22]. However, the most of available literature is concentrated on heavy-duty engines [3] highlighting the necessity of more intensive studies on the application of DF technology to smaller size engines. Moreover, in most of literature there is a lack of data on particle size distributions from DF combustion systems. All research works agree that DF operation leads to a significant reduction of particulate mass concentration with respect to conventional diesel mode but little information is available on the effect of methane addiction to diesel fuel on particle size and number. Nevertheless, particle emissions represent a critical issue in particular for CI engines because of their effect on human health [23]. They were recognized as carcinogen by the World Health Organization [24] and it was demonstrated that particles toxicity increases with decreasing of their size [25]. Moreover, the need to characterize particles emitted from internal combustion engines is driven by the new emission regulations that involve a number based approach in addition to the mass based one [26]. Graves et al. [27] found out that soot aggregates from DF combustion have similar primary particle size, aggregate size, and effective density as diesel soot thus suggesting diesel particulate filter (DPF) as an effective mean to reduce these emissions. The main drawback of the DPF regards the management of the regeneration process. As the particles are trapped, the filer becomes clogged and the exhaust backpressure increases leading to the decrease of the engine efficiency. The loaded soot is eliminated by means of the regeneration during which particle emissions increase as well as fuel consumption [28]. Hence, it is important to reduce the PM emissions just at engine out and to reduce the regeneration frequency. This goal could be achieved by diesel/methane DF technology.

The aim of the paper is the characterization of a diesel/methane dual fuel operation in terms of performance and particle emissions. The novelty of the present research activity consists mainly on the analysis of the effect of diesel/methane DF combustion on particle size and number. The investigation was carried out on a small size CI engine properly 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 while the original electronic control unit (ECU) for diesel injection control was retained. Experiments were performed at the engine speeds of 1600, 2800 and 3200 rpm and at 30%, 50% and 70% of the rated torque output. 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 changing the amount of methane. Combustion behavior of DF combustion was analyzed through indicating data. A smoke meter was used to evaluate PM concentration. The sizing and the counting of the particles were performed in the range from 5.6 to 560 nm.

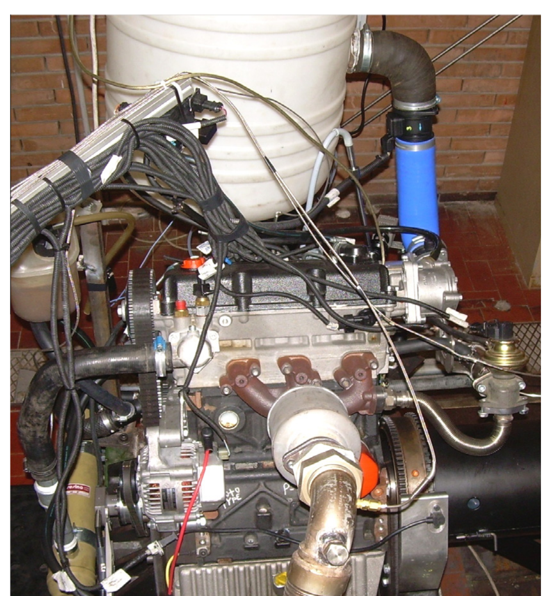

Fig. 1. Test engine.