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Investigation of pilot injection strategy effect on performance and emissions of dual-fuel engine

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Abstract

The dual-fuel combustion is a promising technique for methane utilization in internal combustion. This mode has the potential to reduce emissions of nitrogen oxides and particulate matter. However, this mode presents some deficits at low loads, especially concerning unburned hydrocarbons and carbon monoxide emissions. In the current study, experimental research was conducted to investigate the effect of diesel injection strategy, including single and split injections, on the performance and emissions of a methane/diesel dual-fuel engine.

Keywords: dual-fuel, methane, injection strategy, performance, emissions

Nomenclature

bTDC Before top dead center
ppm Parts per million by volume

1. Introduction

The world today depends on petroleum-based fuels, largely gasoline and diesel, especially in the transport sector. The use of these fuels is expected to decline for two important reasons: the limitations of the worldwide oil reserves and their adverse impact on the environment. [1]. Diesel engines are the most efficient energy conversion devices, but have significant drawbacks: high particulate emissions resulting from the presence of locally over-rich areas near the fuel spray and the high nitrogen oxides (NOx) emissions resulting from the high temperature of the flame in the air-fuel mixture.

Methane is an interesting alternative energy source because of its renewable nature and ecological characteristics. Dual-fuel technology is the most appropriate way to use methane in a compression ignition (CI) engine.

In dual-fuel operation, methane is injected or introduced into the intake manifold as a primary fuel to create a premixed air-fuel mixture, whereas a small amount of diesel fuel (pilot) is directly injected into the cylinder to act as the ignition source. Moreover, this operating mode received a lot of interest due to the simple modification of the conventional diesel engine. However,

there are still some problems limiting the use of dual-fuel engines, especially at low loads [2,3].

Under low load conditions, dual-fuel combustion operates with a very lean air-methane mixture. Under this condition, the flame propagation does not reach the parts of the charge located far from the ignition nuclei because small quantities of diesel are injected. As a consequence, the burning rate slows down, which leads to incomplete combustion and thus to high HC and CO emissions levels [4]. At high engine loads, a sufficiently rich mixture ensures a stable flame distribution over the entire cylinder charge. As a result, a good conversion efficiency is achieved, but the high in-cylinder temperature results in high NOx emissions, comparable to those of conventional diesel engine operation.

Several methods have been proposed to solve the problems related to dual-fuel operation mode. Some of the parameters have a significant influence on the engine efficiency, namely diesel and gaseous injection timings, supply methods and injection pressure [5].

Among these solutions, pilot fuel injection strategy such as injection pressure, injection timing, multiple injection, and others [8] are potentially effective techniques to reduce emissions, because the characteristics of the injection have a significant impact on the combustion process. For example, increased fuel injection pressure results in higher brake thermal efficiency and lower emissions levels, with the exception of NOx emissions, due to improved fuel atomization and, therefore, a better combustion process [9]. Pre-injection contributes to the reduction of combustion noise and NOx emissions, immediate post-injection may also contribute to soot oxidation while late post-injection promotes the regeneration of the diesel particulate filter [6].

In this work, the effect of split/multiple injection is examined experimentally on a methane/diesel dual-fuel engine. Results are compared to conventional diesel operation, which is taken as the baseline.

2. Experimental apparatus and procedure

Experimental tests have been carried out using engine test bench installed in the laboratory of the Energy Systems and Environment Department of IMT Atlantique (Nantes, France). The engine cell is equipped with a single-cylinder AVL 5402 water-cooled diesel engine. The AVL engine is designed to operate at high speed, over a range varying from 0 to 4500 rpm, for a developed power of 6 kW at 4500 rpm.

The engine cell is also equipped with an exhaust emissions bench, a dynamometer, a particle analyzer as well as a gas supply system, which allows the engine to operate in dual-fuel operation mode. Figure 1 is a detailed photograph of the engine cell components.

In order to study the effect of injection strategy, a single injection is first tested. Secondly, a split injection composed of a main and a pre-injection is examined. Three pre-injection timings namely (20, 16, 11 °bTDC) were tested. The amount of pilot fuel injected is divided in two parts. The portion of 20% percent of the total amount of diesel is injected during pre-injection and 80 percent is injected during main injection.

During the experimental tests, pilot diesel fuel is injected to provide 10% of the maximum power. The engine's power is then adjusted by the amount of gaseous fuel while keeping the quantity of liquid diesel fuel constant. Thus, approximately, 0.073 kg/h, 0.21 kg/h, 0.32 kg/h, 0.45 kg/h and 0.58 kg/h respectively of CH₄ flow rates corresponding to 20%, 40%, 60%, 80% and 100% of the full load are examined.

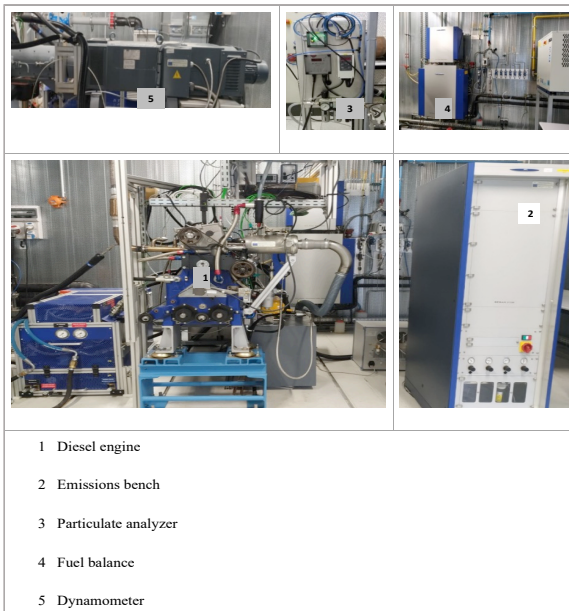


Fig. 1. Test engine bench.

3. Results and discussion

In this section, some results concerning the effect of split injection strategy on performance and emissions pollutant are discussed.

3.1 Combustion analysis

Figure 2 shows the in-cylinder pressure and the heat release rate (HRR), using baseline diesel at 4.5 °bTDC injection timing and methane dual-fuel operation at various pre-injection timings (20,16,11°bTDC) with a fixed main injection timing of 4.5 °bTDC.

Results indicate that HRR profile exhibits a higher peak with single injection strategy than that of split injection cases. It is well known that with a single diesel injection, the first HRR peak usually represents the pilot combustion of diesel, whereas the second peak is due to the premixed combustion of gaseous fuel. In general, first HRR peak is higher than the second heat release peak because methane combustion is slower than diesel combustion. However, under the split injection strategy, less (pre-injected) diesel is used in the first phase of HRR and the mixture of main injected diesel and methane has been ignited simultaneously by the amount of pre-injected diesel, so the second HRR peak increases significantly. For instance, the maximum HRR of the premixed phase is 114.9 J/°CA in the single injection dual-fuel mode (Q_{CH₄}=0.32kg/h) while the maximum value obtained with the split injection strategy is 47.8 J/°CA for a pre-injection timing of 11°bTDC.

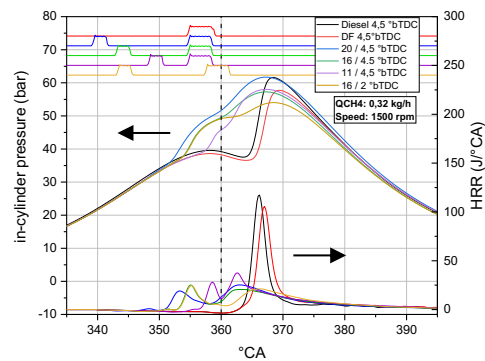


Fig. 2. HRR and in-cylinder pressure versus crank angle.

The intensity of the combustion noise is generally represented as the maximum value of the pressure rise rate (ROPR). Results indicate that split injection further reduces combustion noise. The maximum ROPR value decreases from 0.87 MPa/°CA to 0.25 MPa/°CA at a pre-injection timing of 20 °bTDC, indicating that the first phase of combustion (pre-injected diesel) has been weakened and the second phase of combustion is improved, but is still lower than the single injection strategy, which reduces the combustion noise (Figure 3).

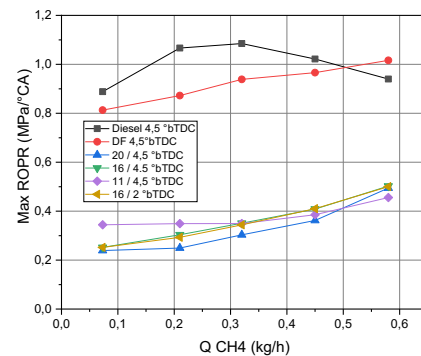


Fig.3 The corresponding maximum ROPR for different injection strategies.

3.2 Performance analysis

Figure 4 shows the variation in brake thermal efficiency (BTE) under various injection strategies. The BTE is shown to be lower in dual-fuel mode compared to conventional diesel for the same injection timing. For instance, at $Q_{CH_4}=0.32$ kg/h, the BTE decreased from 25.4% in conventional diesel to 23.4% in CH_4 dual-fuel mode. However, this difference is reduced by the implementation of the split injection strategy and the results show an improvement at 20 °bTDC pre-injection timing with a BTE equal to 24.7% due to improved combustion of the mixture.

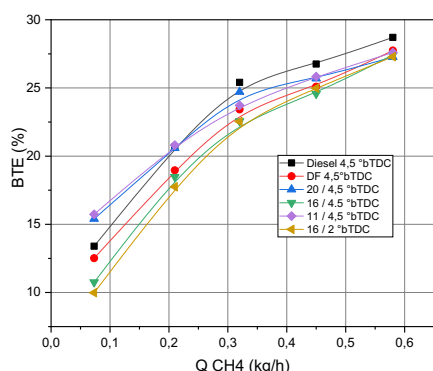


Fig.4 BTE versus different methane mass flow rates for different injection strategies.

3.3 Emissions analysis

Higher NO_x formation is related to higher combustion temperature and higher oxygen concentration. Figure 5 shows the analysis of NO_x emissions. The results show

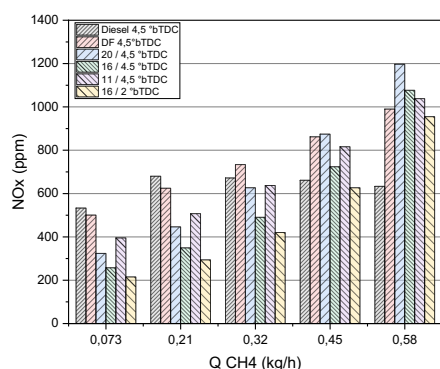


Fig.5 NO_x emissions versus methane mass flow rates for different injection strategies

that NO_x emission concentration increases by increasing engine load. At low load, a higher concentration of NO_x emissions is observed with the diesel engine. At medium to high load, the concentration of NO_x emissions is lower for the diesel engine due to the higher in-cylinder charge temperature. Regarding the split injection strategy, the general trend shows that with a retarded diesel pre-injection timing, NO_x emissions first decrease and then increase for 11°bTDC pre-injection timing.

3. Conclusion

The effect of the pilot injection strategy on the combustion characteristics, performance and emissions of a dual-fuel engine was studied at different CH_4 mass flow rates. The main results are summarized as follows:

- The maximum pressure of the conventional diesel is higher than that of the dual-fuel mode. This difference is reduced by the split injection strategy of diesel until the same pressure is reached. In addition, the occurring position of HRR curve is shifted earlier to TDC compared to the single injection strategy.
- The split injection strategy significantly reduces combustion noise. Advancing the pre-injection timing continuously reduces the combustion noise.
- The BTE of the dual-fuel engine increased with the split injection strategy as a result of an improved combustion process.
- The general trend of NO_x emissions shows that with delayed diesel pre-injection timing, NO_x levels first decrease and then increase for a pre-injection timing of 11°bTDC. At earlier pre-injections, NO_x emissions are highest.

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