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ANALYSIS OF PM AND PN IN DUAL FUEL ENGINE, FUELLED WITH NATURAL GAS AND OME

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DUAL FUEL ENGINES

Introduction

The investigated natural gas-diesel engine is a gas engine where the premixed air-gas mixture is ignited by a small amount of directly injected diesel fuel. The concept can be realized by modifying a production type diesel engine slightly through the addition of natural gas port injectors.

The natural gas-diesel engine has proven its potential of highly efficient operation with low CO_2 emissions on the test-bench of the Institute for Dynamic Systems and Control.

The used engine is a Volkswagen industrial engine with 2 litres displacement volume and 4 cylinder. Since the used engine is a converted conventional Diesel engine, the operation strategy has been adapted in the operation range according to figure 2. Figure 3 shows the energy share of natural gas and pilot Diesel fuel. Even though, the end of injection of pilot fuel is long time before start of combustion, with high share of pilot fuel, significant soot emissions are produced. In the used strategy, this occurred at the lower load range.

Ott T, Onder C, Guzzella L. Hybrid-Electric Vehicle with Natural Gas-Diesel Engine. Energies; 2013; 6: 3571-3592.

Florian Zurbriggen, Richard Hutter, and Christopher Onder. Diesel-Minimal Combustion Control of a Natural Gas-Diesel Engine. Energies, (2016) Basel: MDPI.

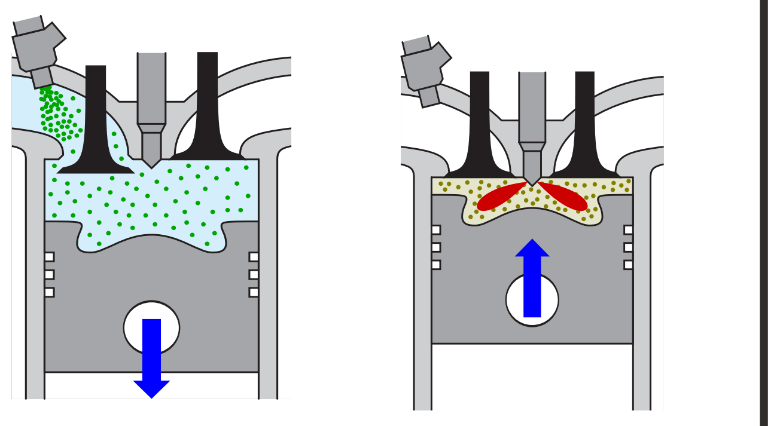


Figure 1: Dual fuel engine, operation principal

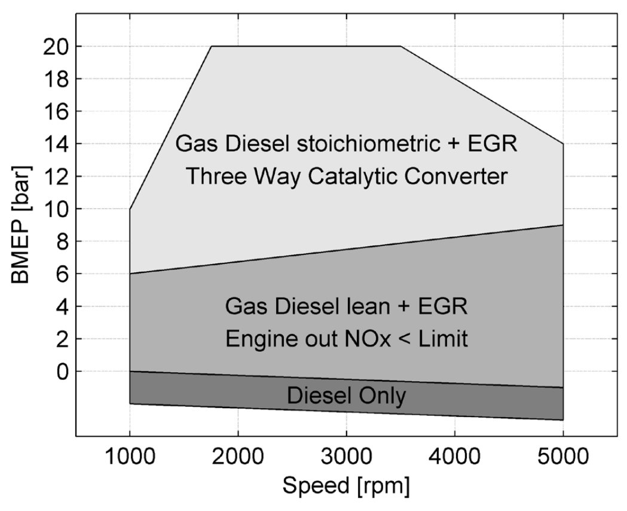


Figure 2: Dual fuel engine, operation strategy

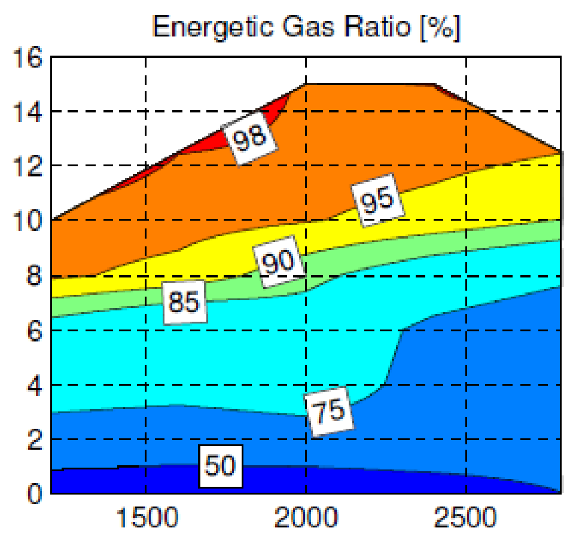


Figure 3: Dual fuel engine, main fuel share

OME AS AN ALTERNATIVE FUEL

OME is the acronym of Polyoximethyldimethylether. The injection, ignition and combustion properties allow the operation in a standard diesel engine without major modifications. The precursors are producs from a power to liquid process with a very small CO_2 footprint.

Structure of OMEn:

$CH_3 - O - [CH_2 - O]_n - CH_3$

For the synthesis two building blocs are required:

CH_3 – Cap groups: from Methanol (CH_3OH) or DME (CH_3OCH_3)

CH_2O – Monomers: from Formaldehyde (CH_2O) or Trioxane ($C_3H_6O_3$)

Present production route via Trioxane/OME1:

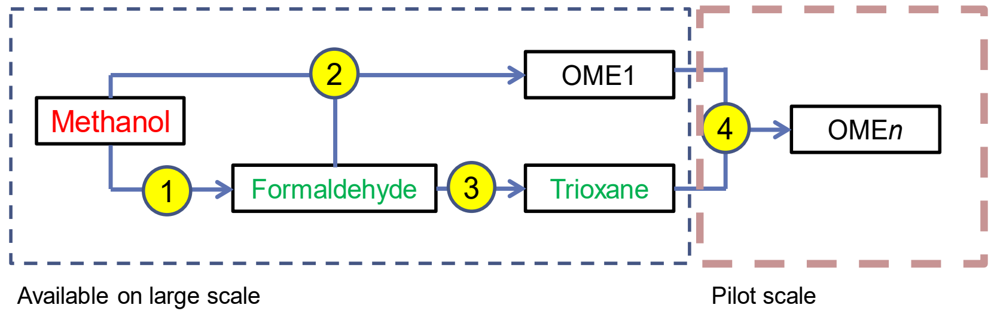


Figure 4: OME production route

Details of Process 4:

Process available (BASF / TU Kaiserslautern)

Product chain length adjustable freely

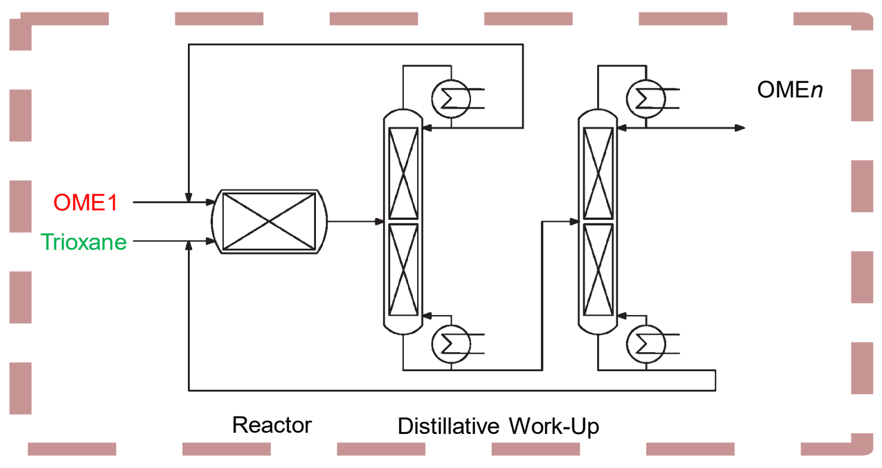


Figure 5: OME production step 4 in detail

J. Burger et al., "Production process for diesel fuel components poly(oxymethylene) dimethyl ethers from methane-based products by hierarchical optimization with varying model depth", Chem. Eng. Res. Des. 91, 2648-2662, 2013.

Production Costs of OME:

Strongly dependent on methanol price

Example: OME3-5 via Trioxane/OME1 route

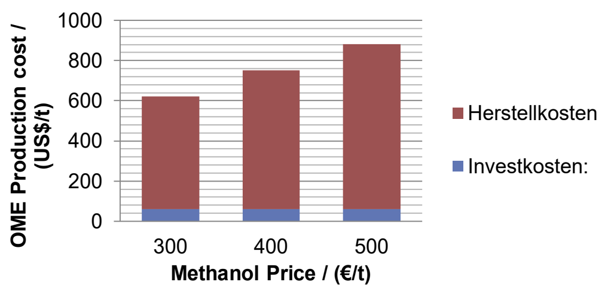


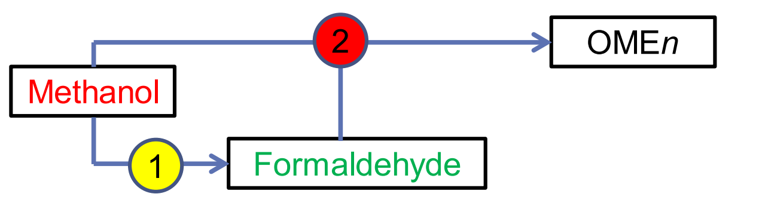
Figure 6: OME production costs

N. Schmitz et al., "From methanol to the oxygenated diesel fuel poly(oxymethylene) dimethyl ether: an assessment of the production costs", Fuel (submitted), 2016.

Future Production of OME

Numerous research activities. Two examples:

Direct route via Methanol/Formaldehyde. Step 2 under research:



Usage of DME. Step 2 under research:

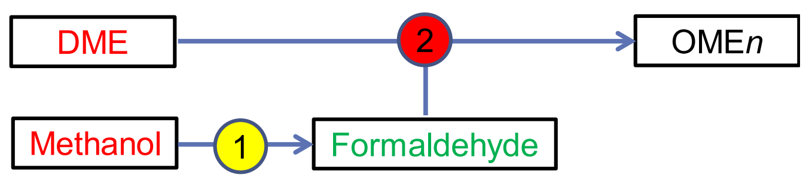


Figure 7: OME production; future productlon steps

DUAL FUEL ENGINES WITH OME

Comparison of OME and Diesel

Figure 8 compares the heat release rates of an operating condition at 1600 rpm and 8 bar brake mean effective pressure (BMEP) with either Diesel or OME as pilot fuel with similar injection settings (This means: similar fuel mass but different energy share). The global stoichiometry is one for both pilot fuels. At this load, the percentage of pilot fuel is already very low, thus, lower energy content of OME only minor influence the stoichiometry of the premixed natural gas. However, the impact of the pilot fuel on the combustion is very high. The ignition delay is lower due to the higher cetane number and the natural gas combustion is faster. The latter effect can be attributed to the higher temperature, since the combustion is closer to top dead center. Furthermore, the stoichiometry of the natural gas is closer to 1 which increases the flame speed.

Figure 9 shows a lower load condition at only 5 bar. The comparison shows a the operation condition with the minimum possible amount of pilot fuel. In the Diesel case, this is 37% of the total energy share. In the case with OME it is only 7%. Especially for cases with low load, the dilution of the pilot spray has an important effect on the ignition delay. The energy share of OME is significantly lower, due to a lower ignition delay. This can be attributed to the combination a higher cetane number and the lower heating value, which reduces the effect of dilution. The combustion behaviour of OME under engine like conditions can be found in:

S. Iannuzzi, C. Barro, K. Boulouchos, J. Burger, Combustion behavior and soot formation/oxidation of oxygenated fuels in a cylindrical constant volume chamber, Fuel, Volume 167, 1 March 2016, Pages 49-59

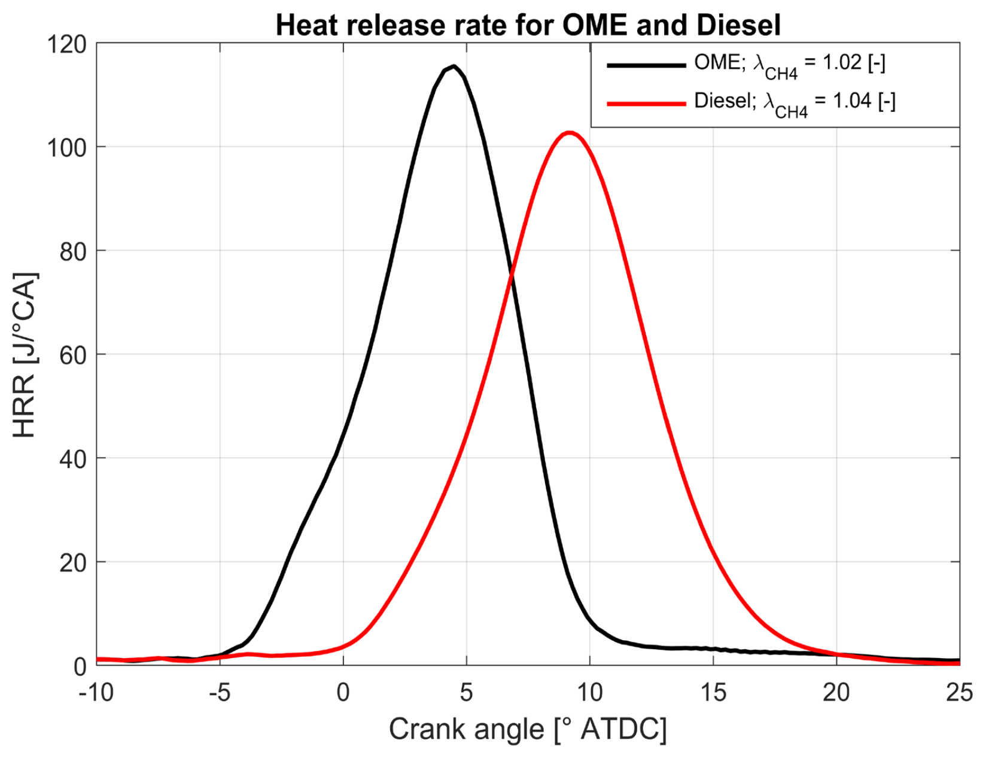


Figure 8: Heat release rates of natural gas combustion, ignited with OME (black) and Diesel (red) with similar injection settings.

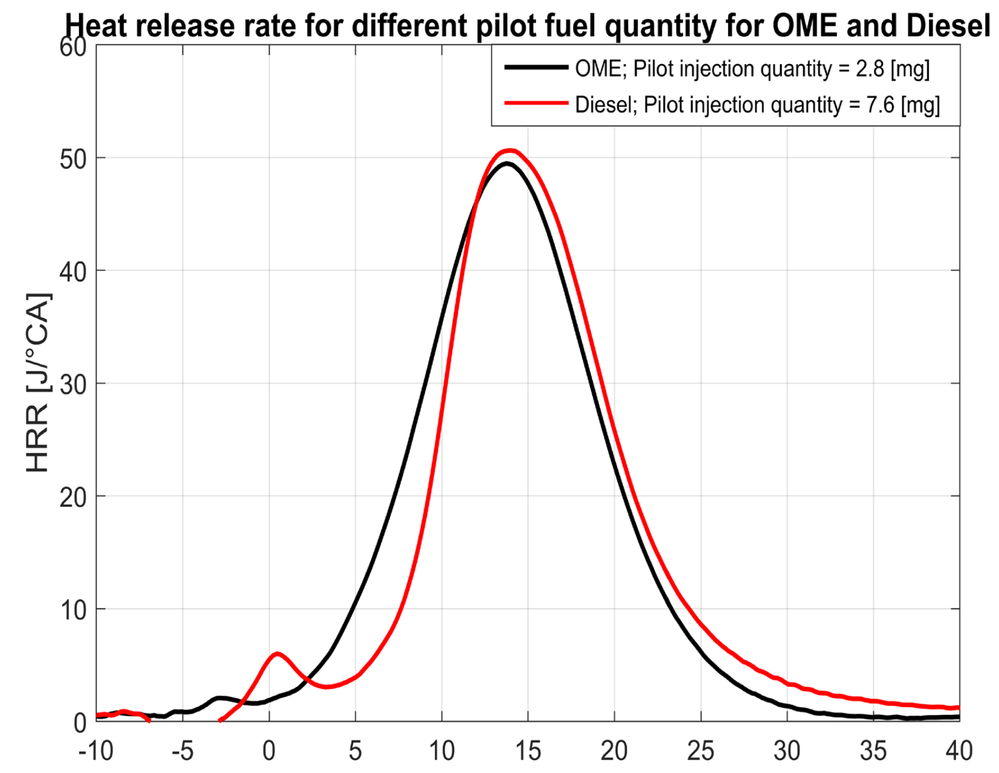


Figure 9: Heat release rates of natural gas combustion, ignited with OME (black) and Diesel (red) using the minimum possible amount of pilot fuel for similar combustion behaviour.

Particulate Matter (PM) and Particulate Number (PN) Emissions

In the lower load operating condition, as depicted in figure 3, the share of pilot fuel can be up to 50%. The large amount of pilot fuel causes two major effects. The mixture of natural gas needs to be very lean (slow flame speed) and the core of the auto-ignition zone is fuel rich. The latter one cause high PM emissions. The figures 10 and 11 show a comparison between 4 different engine settings at 4 bar BMEP with high EGR ratios, according to table 1.

OP 1: 1500 rpm, 4 bar BMEP, 35% EGR, Swirl no
OP 2: 1500 rpm, 4 bar BMEP, 35% EGR, Swirl yes
OP 3: 2000 rpm, 4 bar BMEP, 40% EGR, Swirl no, DOI 700 µs
OP 4: 2000 rpm, 4 bar BMEP, 40% EGR, Swirl no, DOI 600 µs

Table 1: Operation condition characteristics

PM has been recorded using an AVL Micro Soot Sensor, the spectral particulate number distribution has been recorded with a Cambustion DMS 500. Figure 10 shows, that measures like swirl addition or reduction of the pilot injection duration help to reduce PM emissions, but the level remains high. Furthermore, the figures, 10 and 11 show that, both, PM and PN are orders of magnitudes lower using OME instead of Diesel as a pilot fuel. This is attributed to the oxygen content of OME, inhibiting soot formation. Using OME, only OP1 shows detectable PN level. However, the size range indicates that the recorded particles are most likely of volatile nature. OME shows a huge potential to reduce PM/PN emissions during low load operation of dual fuel engines.

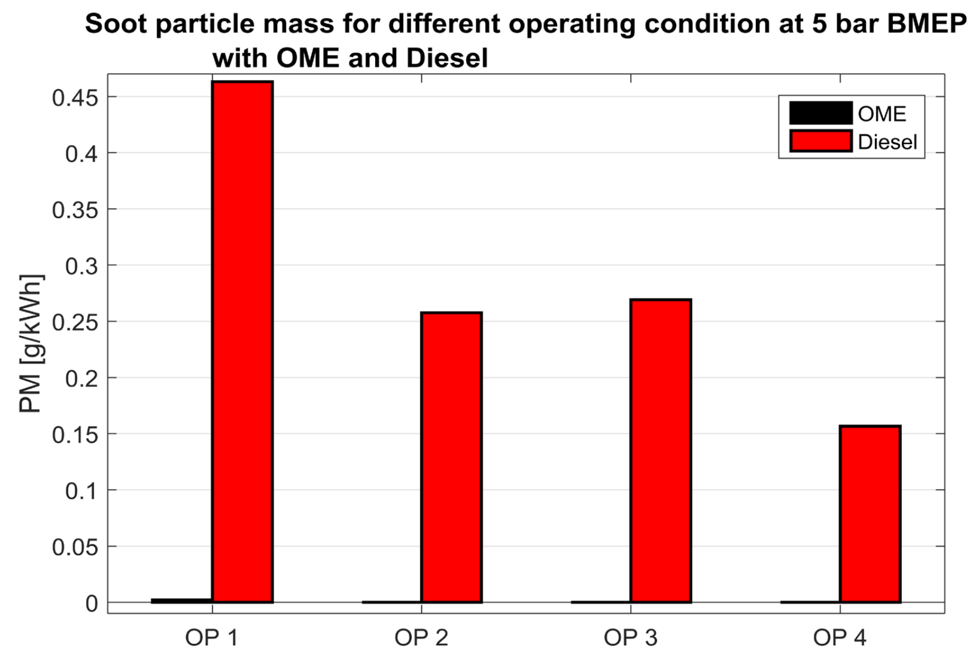


Figure 10: Comparison of PM emissions of OME (black) and Diesel (red)

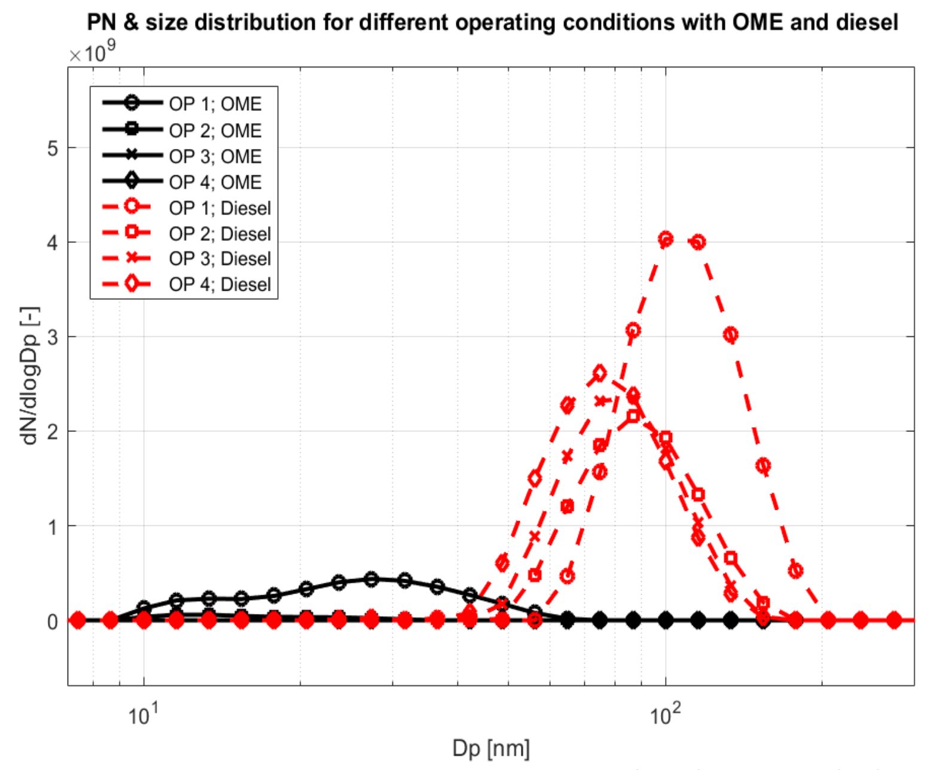


Figure 11: Comparison of spectral PN emissions of OME (black) and Diesel (red)

CONCLUSION AND OUTLOOK

A dual fuel engine has been operated with natural gas, premixed as main, and Diesel as well as OME as pilot fuel. The used OME blend contains OME 2, OME 3 and OME 4. This particular blend has an approximatley 15 % higher density and 50% lower energy density than Diesel (due to its oxygen content). Furthermore, the OME blend has a higher cetane number. The operations with OME as pilot fuel show shorter ignition delays and a faster combustion in comparison to similar operating conditions with Diesel. Using Diesel, the operation in the lower load range requires a high share of pilot fuel. This has a negative effect on the CO_2 as well as on soot emissions. Due to the shorter ignition delay, the operation with OME allows a higher share of main fuel. Moreover, the oxygen content of the fuel inhibits formation of soot almost completely. Therefore, the exhaust emissions of the operating conditions with OME do not show PM or PN.

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