EXPERIMENTAL INVESTIGATION OF DIFFERENT COMBUSTION MODES IN A SINGLE-CYLINDER DUAL-FUEL CI ENGINE

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ABSTRACT

In this study, the effects of different diesel injection strategies on methane / diesel-dual-fuel (DDF) combustion are experimentally investigated. In order to enhance the fundamental understanding of the in-cylinder process, the impact of DDF key control parameters, i.e. injection timing, injection duration, and substitution rate (80 – 90 %) on the combustion phasing and pollutant formation is examined, while engine speed, global equivalence ratio, and injection pressure are held constant. The results reveal regimes that show different dependencies between injection timing of diesel fuel and combustion phasing. It was found that early injection timings lead to reduced NO_x, THC, and soot emissions at simultaneously improved thermal efficiencies. The increase in thermal efficiency has been further investigated by analyzing the engine losses with a 0D thermodynamic engine model, indicating that early injection timings reduce non-ideal combustion losses. To summarize, this study shows that diesel-dual-fuel operation is a promising combustion mode to counteract the drawbacks of compression ignition engine.

INTRODUCTION

Compression ignition (CI) engines have higher efficiencies than spark ignition (SI) engines, caused by high compression ratios and avoided throttling losses [1, 3]. However, the non-premixed combustion process in CI engines can lead to high emissions of nitric oxides (NO_x) and particulate matter (PM). For reduction of those emissions, exhaust-after-treatment devices are required for modern CI engines, which can increase fuel consumption and costs [4, 6]. To reduce the engine-out emissions and the operating costs, while ensuring high levels of overall engine efficiency, advanced combustion strategies are required [3, 4, 6]. One of those strategies is the diesel-dual-fuel (DDF) concept. By employing two fuels with different auto-ignition characteristics, e.g. port fuel injection of a low-reactivity fuel (natural gas) and direct injection of a high-reactivity fuel (diesel), it is possible to reduce the engine-out emissions while keeping high thermal efficiencies.
Depending on the injection timing of the high reactivity fuel, two different

combustion modes – reactivity-controlled compression ignition (RCCI) and dual-fuel (DF) – can occur [7]. In RCCI mode, the diesel fuel is injected very early during the compression stroke and a stratification in reactivity is generated within the combustion chamber. In DF mode, the diesel fuel is injected close to TDC yielding a compression ignition that is used to initiate a propagating flame front like in SI engines [7]. In this work, in-cylinder fuel blending with premixed methane / air-mixture and direct injection of diesel fuel is investigated. Methane is chosen as a supplement to diesel fuel, due to its benefits like higher knock resistance, cleaner combustion, availability, and higher auto-ignition temperature [8].

EXPERIMENTAL SETUP

The experiments in this study were conducted in a modified single-cylinder research engine (SCE) that is based on a DV6 TED4 production engine. For the DDF investigations, the compression ratio is reduced from 17.4:1 to 15.1:1 and the piston bowl geometry is changed from a re-entrant type to a flat piston bowl geometry. The relevant engine and injector parameters are listed in Table 1 and a schematic test bench layout is illustrated in Figure 1.
The air supply is ensured by an external unit consisting of three EATON M62 compressors with inter-coolers. Auxiliary systems for heating or cooling oil, water, air, and fuel are applied to the test bench in order to maintain well-defined conditions. The load is represented by a DC motor (speed-controlled) equipped with a torque meter. For controlling the engine (i.e. intake pressure, exhaust pressure, injection timing, duration, cylinder pressure, etc.), a customized engine control unit (ECU) is used. The exhaust gas was collected using a heated probe and emissions data including NO_x, THC, CO, CO_2, O_2, and soot are metered in the appropriate analyzers. Simultaneous measurements of the air-fuel-ratio (AFR) and the external EGR-rate are performed by the EGR 5230 module. The single cylinder engine is equipped with a piezoelectric pressure transducer (mounted via a glow plug adapter) in conjunction with the charge amplifier. Hereby, reliable thermodynamic data determination is ensured. The analysis of in-cylinder parameters, e.g., indicated mean effective pressure of the high-pressure process ($IMEP_{HP}$), combustion phasing (CA50), and heat release rate (HRR) were evaluated in a thermodynamic real-time analysis module (TRA) for 100 consecutive cycles.

Table 1 Engine and injector specifications.

Quantity	Value	Unit
Displaced volume	390	ccm
Stroke / Bore	88.3 / 75	mm
Compression Ratio	15.1:1	-
Number of Cylinders	1	-
Swirl Number	1.386	-
Nozzle (#/∅)	6/142	-/µm

Figure 1 Schematic of the test bench layout.

Experimental Results

In this section, the experimental results are presented in the following order:

- CA50 as a function of start of energizing (SOE) and substitution rate (SR)
- In-cylinder data for early and late branch

Figure 2 summarizes the results for variations in SOE for SR ranging from 80 to 90 %. Starting at -15 °CA aTDC, the SOE is advanced up to -55 °CA aTDC with an increment of approx. 3 °CA. The engine speed, equivalence ratio, injection pressure, and methane mass flow are held constant. Furthermore, different dependencies between CA50 and SOE as well as between CA50 and the amount of injected diesel fuel are revealed in Figure 2. For describing the process characteristics, e.g. for the 2.2 mg/stroke case (SR= 90 %), the depicted curve is divided into three areas. In the interval from -15 °CA aTDC to -30 °CA aTDC, the local sensitivity is found to be positiv $\frac{\partial CA50}{\partial SOE} > 0$, i.e. an advancement of SOE leads to an advancement of CA50. This area is referred to as late branch and is designated with injection timings closer to TDC. Further advancement of SOE results in $\frac{\partial CA50}{\partial SOE} = 0$, which is referred to as reversal point and characterized by the earliest CA50, i.e. 7 °CA aTDC, that is achieved. For injection timings beyond the reversal point, i.e. earlier than -35 °CA aTDC, the combustion is retarded and a sign-inversion of the local sensitivity, i.e. $\frac{\partial CA50}{\partial SOE} < 0$, is observed, which is referred to as early branch (cf. Figure 2).

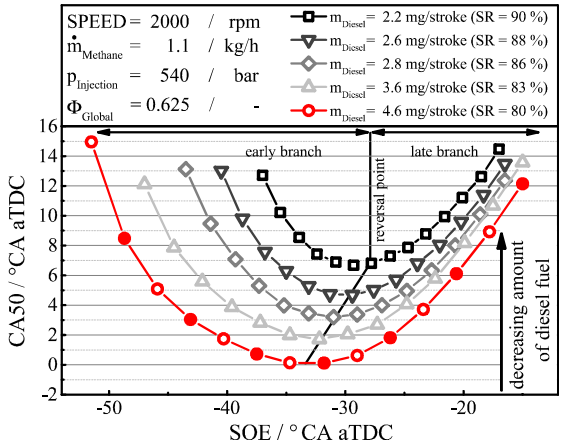

Figure 2 CA50 as function of injection timings and substitution rates, engine speed, equivalence ratio, injection pressure, and methane mass flow are held constant.

The retarding of CA50 on the early branch can be explained by changing ratios of chemical and mixing time scales. For early diesel injection timings more, time is available for premixing prior to ignition due to long ignition delays at lower temperatures and pressures. Hence, leaner local fuel-air mixture are present, which delays the ignition even further [9]. In order to get more detailed understanding of the combustion process, the in-cylinder data, i.e. cylinder pressure and heat release rate (HRR) for the late (left) and early branch (right), is given for a constant SR of 80 % in Figure 3. For the late branch, the injection timings -15 °, -18 °, and -26 °CA aTDC are shown, while for the early branch the injection timings -38 °, -43 °, and -49 °CA aTDC are depicted (filled circles in Figure 2). For both cases the reversal point that occurs at an injection timing of -32 °CA aTDC is included

On the late branch, an increase in combustion pressure is observed for advanced injection timings with a maximum cylinder pressure of 130 bar, that is achieved in the reversal point curve. On the contrary, if the injection timings are advanced for the early branch - starting at the reversal point - the maximum cylinder pressure decreases. Interestingly, the rate of change in pressure is smoother for the early branch compared to the late branch. The decrease in the cylinder peak pressure for the early branch can be explained by the increased ignition delay times caused by leaner mixtures. Longer ignition delay times can shift the combustion towards the expansion stroke [8]. The HRR profiles clearly visualize the different combustion modes. For the late branch, a process similar to conventional diesel combustion, consisting of a rapid pre-mixed combustion close to TDC and a pronounced non-premixed combustion tail, is observed. The characteristic of the HRR can be divided in three parts. First, the ignition of the diesel fuel is observed (peak in the HRR), followed by the ignition of the methane air mixture in the vicinity of the diesel spray (reduced HRR) that finally result in a propagating premixed flame [10]. The contribution of the different parts to the accumulated heat release changes with

varying injection timings, e.g. for an advancement of the late injection timings the peak in HRR increases, while a decrease in the combustion tail is determined. The maximum HRR peak is achieved in the reversal point, while the occurrence of pre-combustion is detected. The pre-combustion is observed for all injection timings on the early branch. Furthermore, with earlier injection timings on the early branch a remarkable change in shape of the HRR is noticed. The previously mentioned characteristic combustion parts are no longer visible, which might be related to the more homogenized diesel-methane-air mixture that result in predominantly premixed flame combustion. The described dependencies are observed for all considered SR in this work. However, the CA50 shifts towards earlier timings with increasing diesel mass and the position of the earliest CA50 moves towards earlier injection timings, which is related to the increased time to promote a lean mixture (cf. Figure 2). To summarize, the indicated efficiency is influenced by CA50 and the SR, while SR has a stronger impact. Highest efficiencies (approx. 48.5 %) are achieved for CA50 close to TDC, on the early branch, and for the lowest SR. A retarding combustion to later CA50 leads to a decrease in the efficiency.

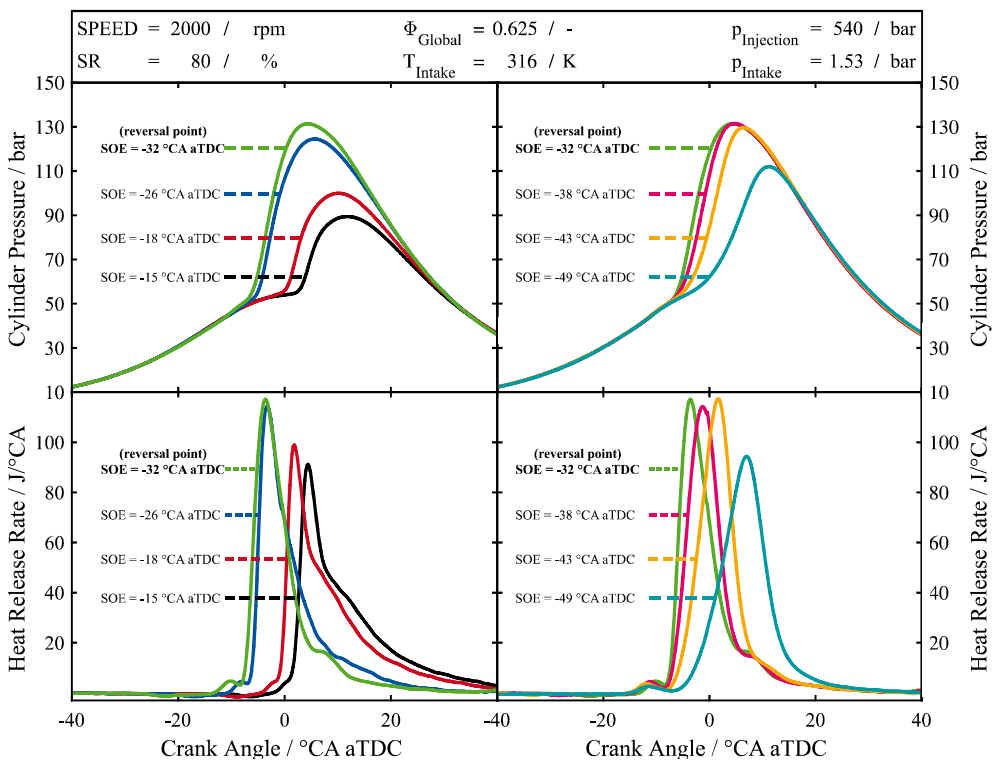

Figure 3 In-cylinder data, i.e. cylinder pressure and HRR, for different injection timings on the late branch (left) and on the early branch (right). Additionally, the reversal point is shown for both injection timings.

Summary and Conclusion

In this work, the effects of different diesel injection strategies on methane / diesel-dual-fuel (DDF) combustion have been experimentally investigated in a compression ignition engine. The engine has been operated with premixed gas / air charge and direct injection of diesel fuel. Variations in injection timings, injected fuel mass, and substitution rates have been conducted and evaluated. The results revealed different dependencies between combustion phasing and the injection timing of the diesel fuel. The in-cylinder pressure and heat release rates have been analyzed in more detail for a single substitution rate. For injection timings close to TDC, a process like the conventional diesel combustion process, consisting of a rapid pre-mixed combustion close to TDC and a pronounced combustion tail, were detected. In contrary, for early injection timings, a remarkable change in the shape of the HRR was noticed, which indicate the combustion of a more homogenized diesel-methane-air mixture with predominantly premixed combustion.
Overall, the highest indicated efficiencies were achieved for early injection timings and low substitution rates.

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