Optical analysis of the combustion of potential future E-Fuels with a high pressure dual fuel injection system

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ISBN Nummer 978-3-9816971-6-2

Introduction

Due to efforts to mitigate global climate change, decarbonization is nowadays a key driver in energy technology and the development of mobile power¬trains. While in the passenger car segment the focus of many companies is on battery electric drives, such drives seem not to be suitable for many applications where much larger amounts of energy have to be stored (e.g. trucks, off-road applications, or shipping). Energy storage using synthetic fuels produced from renewable electricity and eventually carbon sequestered from the atmosphere seems to be the most viable option here. Table 1 shows important properties of such possible E-Fuels. In order to be widely used in the future, a good storeability, but also a simple and above all cost-efficient production is essential. The fuel easiest to produce is hydrogen which is also necessary for the production of all other E-Fuels mentioned in Table 1. Since hydrogen is extremely difficult to store in large quantities, the other fuels listed are nevertheless interesting, although their production requires additional effort. The boiling point gives an idea about the efforts needed to store the listed fuels. The carbon content is relevant, since carbon for the production of CO2-neutral fuels should be extracted from the ambient air by "direct air capture" - which is a relevant cost driver.

Table 1 – Properties of potential future E-fuels

	Chemical Formula	Lower heating value	Boiling point	Carbon content
	[-]	[MJ/kg]	[°C]	[gC/MJ]
Hydrogen	H2	119.9	-252	0
Methane	CH4	50.0	-162	15.0
Methanol	CH3OH	19.9	+65	18.8
Ammonia	NH3	18.6	-33	0
N-Heptane (~ Diesel)	C7H16	45	+98	18.7

For ship engines, direct Injection and diesel-like mixing-controlled combustion is a good option for all of the discussed E-Fuels. With the "High pressure dual fuel" (HPDF) concept, the main (E-) fuel is injected with high pressure (300…500bar) at the end of the compression stroke, and ignited by the combustion products of a small diesel pilot injection that occurs typically slightly before the main fuel injection. Compared to premixed combustion systems, mixing-controlled combustion has the advantage of a very good controllability of the combustion of a wide range of fuels. In addition, the slip of unburned fuel due to the absence of fuel in the fire land or quenching zones near the walls is significantly reduced. This is especially relevant when methane is used as fuel, as emissions of unburned methane contribute with a factor of 28 (on a 100-year-basis) to global warming compared to CO2 [1].

The "HPDF" engine concept in large high-speed engines was initiated by MTU Friedrichshafen / Rolls-Royce Power Systems. It was setup and investigated on various levels together with the Technical University of Munich and Woodward L'Orange [2-11]. Already in an early project phase, fundamental studies on the interaction of a single high-pressure gas jet and a diesel pilot spray were conducted at the Institute of Thermodynamics at the Technical University of Munich (TUM) [2-4]. Based on these findings, Woodward L'Orange has developed an experimental "HPDF"-Injector (Figure 1) with the capability of injecting a low-calorific main fuel, as well as a small quantity of pilot diesel at independent pressures and timings [5,6]. When the first prototype injectors became available at a later stage of the project, HPDF combustion was investi-gated under realistic high-load operating conditions in a fully optically accessible 4.8L research engine at the Chair of Internal Combustion Engines (LVK) at TUM [7], for the purpose of validation and further development of suitable CFD models [8-10]. Detailed investigations on emissions and efficiency of the combustion process are being carried out on a thermodynamic single-cylinder research engine from MTU Reman Technologies / Rolls-Royce Power Systems [11, 12].

In this article, after a short introduction of the Woodward L'Orange HPDF Injector and a description of the optical engine and measurement setup, a comparison of methane, methanol and hydrogen HPDF-combustion is shown. Since ammonia is easy to store and does not require Carbon for its production, it is also very often discussed as fuel for ship engines. However, due to its toxicity, ammonia would have required a much more advanced safety system at the test bench, and is therefore not part of this study.

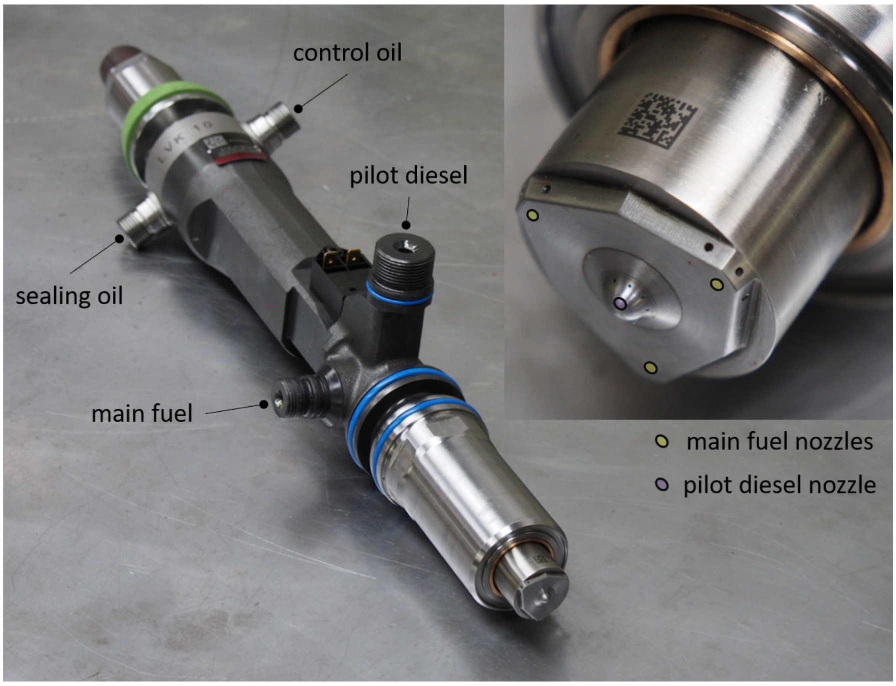

Figure 1 – high pressure dual fuel injector from Woodward L'Orange

High pressure dual fuel injector

The Woodward L'Orange high pressure dual fuel injector which was used in this work is shown in figure 1. The injector tip contains a central diesel nozzle for pilot diesel injection, and three gas nozzles which are arranged around the diesel nozzle. Unlike "HP-DI"-Injectors that are already built and commercially sold for some time for truck-sized engines [13], the diesel and gas subsystems are independent from each other in the Woodward L'Orange injector. This has the advantage that the pilot diesel injection pressure can be set independently from the main fuel (gas / methanol) injection pressure, and that a diesel-only operation is also possible. For the experimental version of the HPDF-Injector used in this work, a control oil and a sealing oil pressure have to be applied to two extra connectors. The control oil is needed for the electro-hydraulic actuation of the 3 gas needles, whereas the sealing oil is needed to seal the gas (or main fuel) path within the injector. More detailed information about the design and working principle of the Woodward L'Orange HPDF-Injector can be found in [5, 6].

Experimental Setup

In figure 2, the large bore optical accessible research engine is shown. The engine is self-developed by the Chair of Internal Combustion Engines of the TUM, and with a bore of 170mm and a stroke of 210mm it has a displacement of 4.8l. During the initial design, as well as in later further developments, one of the main goals was to enable high cylinder peak pressures. This is important for the transfer of the gained knowledge to real engine operation, because engines in this power class (which are used e.g. in ships, locomotives, mining, ...) are often operated at high loads for large portions of time, and therefore operating points with high loads have a great influence on both fuel consumption and emissions over the total operating time. The engine has two optical accesses – one lateral access in the upper part of the cylinder liner for illumination, and one for imaging in the upper part of the elongated "Bowditch-design" optical piston. For a combustion chamber geometry similar to that of a normal diesel engine, a cylindrical bowl is manufactured in the piston glass insert, whereby the bowl volume is optically accessible for illumination from the side in TDC. For the investigations described here, light from the combustion chamber is split into a visible wavelength range and a UV portion, and imaging is done with two high-speed cameras: One camera is a monochrome version that detects UV light emission from the OH-Radical in combination with an image intensifier and a 300-320nm bandpass filter. The other camera is a color version that detects light in the visible wavelength range, which is predominantly soot light emission from sooting flames. Also, on the blue channel of the camera, Mie-scattering of liquid fuel sprays is recorded. The illumination therefore is done by a blue LED light source that was developed at the institute. A more detailed description of the optical engine and the imaging system is available in [7].*

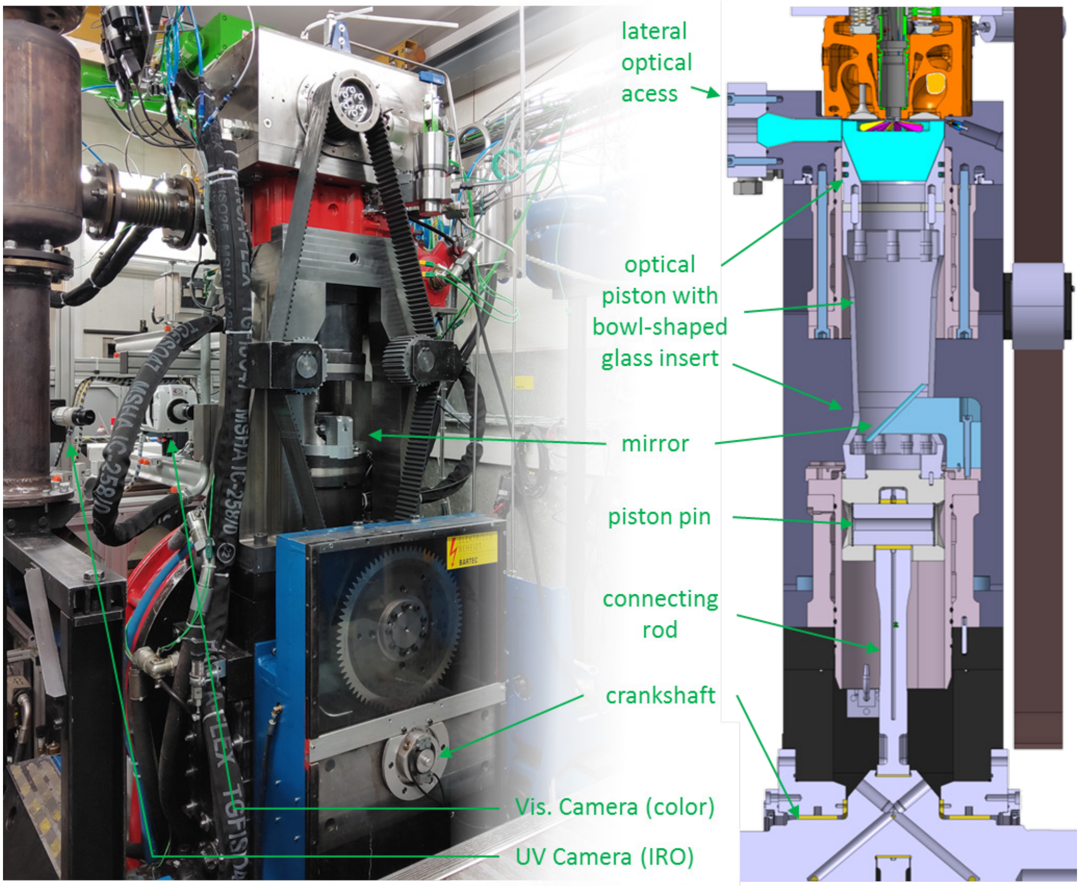

Figure 2 – 4.8l optical accessible research engine

Comparison of Methane, Methanol and Hydrogen combustion

For a characterization of the combustion of methane, methanol and hydrogen in a HPDF combustion process, these fuels were tested in the optical engine under the same operating conditions. Only the energizing duration for the main fuel was adapted in order to get the same amount of fuel energy into the combustion chamber. The operating para¬me¬ters are shown in table 2. The main fuel energizing durations were previously deter-mined in test injections under atmospheric conditions in order to get a fuel energy of ~27.5 kJ per injection. From the apparent released heat traces shown in Figure 3, it can be seen that the amount of injected fuel energy is obviously different under fired operating conditions. For methane and methanol, the apparent released

Table 2 - operating parameters for the comparison of different fuels

		CH_4	CH_3OH	H_2
engine speed	[rpm]	750		
boost pressure	[bar]	6.5		
exhaust pressure	[bar]	5.2		
Camshaft	-	Miller (IVC ~60° b.BDC.)		
Air mass	[g/cycle]	18.5		
Main fuel mass (target)	[mg/Inj.]	550	1380	230
$p_{Rail, Main Fuel}$	[bar]	500		
$t_{Energizing, Main Fuel}$	[ms]	1,40	1,70	2,70
Pilot diesel mass	[mg/Inj.]	10...15 (~ 2.5% of total fuel energy)		
$p_{Rail, Diesel}$	[bar]	1200		
$t_{Energizing, Diesel}$	[ms]	0,464		
Air fuel ratio (target)	[-]	1.90	2.02	2.26

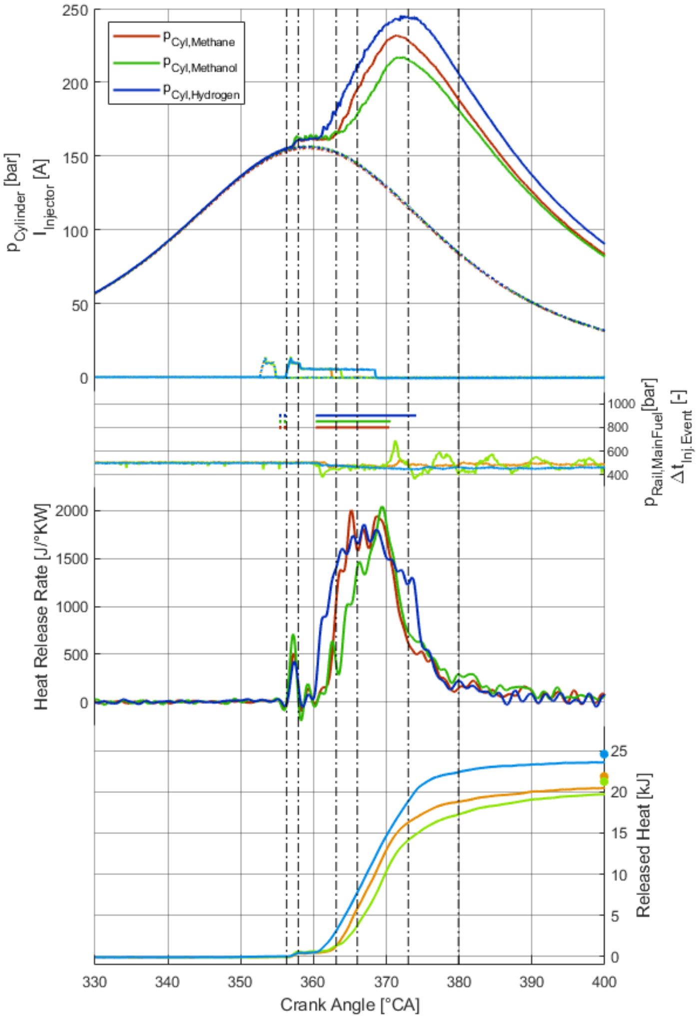

Figure 3 - Cylinder pressure traces and heat release rates for different fuels with HPDF combustion

heat is at ~80% of the previously determined value, while for hydrogen it is at ~90%. For methanol there is an easy explanation for this observation, as an increasing counter-pressure reduces the injected mass according to the Bernoulli formula. For methane and hydrogen, according to the laws of gas dynamics (which are only an approximation since the gases are in a supercritical state under the given conditions), there should be no influence since the ratio between rail and combustion chamber pressure is always above the critical value. In reality, however, there is obviously an influence, which also seems to be less significant for hydrogen than for methane. For the methane and methanol cases, the IMEP is therefore at ~22 … 23 bar, while for the hydrogen case it is at ~26 bar.

Figure 4 shows the pressure traces, heat release rates and released heat for the 20th fired cycle of each operating point, and figure 5 shows the image of the color camera at the indicated crank angles for the same cycle.

As can be expected, the pilot diesel injections and combustion are nearly identical for all operating points. With the very small pilot quantity, the penetration depth of the pilot spray is slightly asymmetrical. How¬ever, considering the fact that the diesel nozzle is designed for a full load injection, the spray quality is remarkably good at this very low injection quantity of only ~2.5% energy content, and with the HPDF combustion process definitively sufficient for a stable ignition of all the tested fuel types. Like the diesel spray, also the methanol and gaseous main fuel injections show a clear Mie-scattering signal on the color camera images. For the gaseous fuels, this has two possible reasons: On the one hand, due to the design principle of the injector, some sealing oil is leaking into the gas path and is injected with the main fuel. On the other hand, both hydrogen and methane are supercritical at the injection conditions of T=80°C and pressures above 50bar. Therefore, also the gaseous fuels may scatter light at the given conditions. From the optical recordings it can be seen that the main injection starts at 360°CA in all three cases. From the heat release rates, it can be read that methane and methanol both have an ignition delay of about 3°CA from this point on. For methanol, possibly due to the required evaporation enthalpy, it takes some additional time until the heat release rate reaches the level that is reached with methane. For hydrogen, there is almost no ignition delay. The heat release rates show that with methane and methanol, a large proportion of the heat release (35–40%) only takes place after the end of injection (which is at 370°CA in

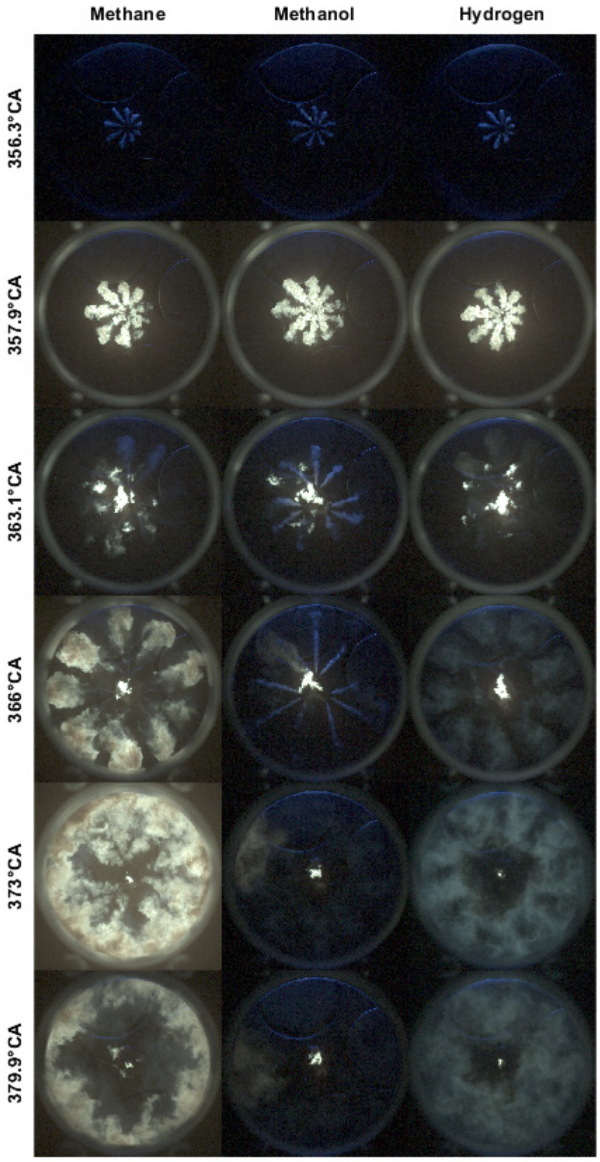

Figure 4 - recordings from the color camera for CH4, CH3OH and H2

both cases). For hydrogen, the portion of fuel that burns after the end of injection (at 374.5°CA) is substantially lower. With methane, sooting diffusion flames develop shortly after the gas jets entering the combustion chamber are ignited. The burning gas jets then hit the walls of the piston bowl and form fuel-rich zones in the outer area of the piston bowl. Especially after the end of injection, the mixing of air into these zones becomes more difficult. This leads to a burn-out phase typical for mixing-controlled combustion systems. Also, due to this local lack of air, some of the soot that has been produced in the combustion process so far is not completely oxidized. At 380°CA, those fuel-rich sooty flame areas can be seen near the walls of the piston bowl. Parts of the soot near the piston bowl walls are still not oxidized until the end of the optical recordings at 405°CA, and it is likely that this soot identified in the optical recordings in this late combustion phase corresponds to a large extent to the soot emissions measured in the exhaust. It should be noted however, that with HPDF combustion systems, soot formation can be greatly influenced by the relative timing of the gas and pilot diesel injections (i.e. the degree of gas premixing) [10, 13], and that air entrainment and soot oxidation are strongly dependent on the piston bowl geometry, where the cylindrical shape in the optical engine is just a very simple and probably not optimal case. Nevertheless, the recordings from the optical engine offer the possibility of a good understanding of the general phenomena, and are a good basis for the calibration of CFD models under realistic conditions.

In the case of methanol, the fuel jets initially appear to entrain some soot from the diesel pilot flame as they enter the combustion chamber. However, no further soot is produced by the combustion of methanol. The liquid methanol fuel jets penetrate far into the combustion chamber and evaporate in the flame which is invisible on the color camera pictures. The flame is still visible on the OH pictures which are not shown here, but also indicate that fuel-rich zones build up in the outer areas of the piston bowl, and the main portion of heat release occurs in the mixing layer between those fuel rich zones and the air between the fuel jets and in the center of the combustion chamber. For hydrogen, the burning gas jets also seem to entrain some soot from the pilot diesel combustion, but otherwise burn in an (in the visible wavelength range) almost invisible flame at the beginning (363.3°CA). In the*

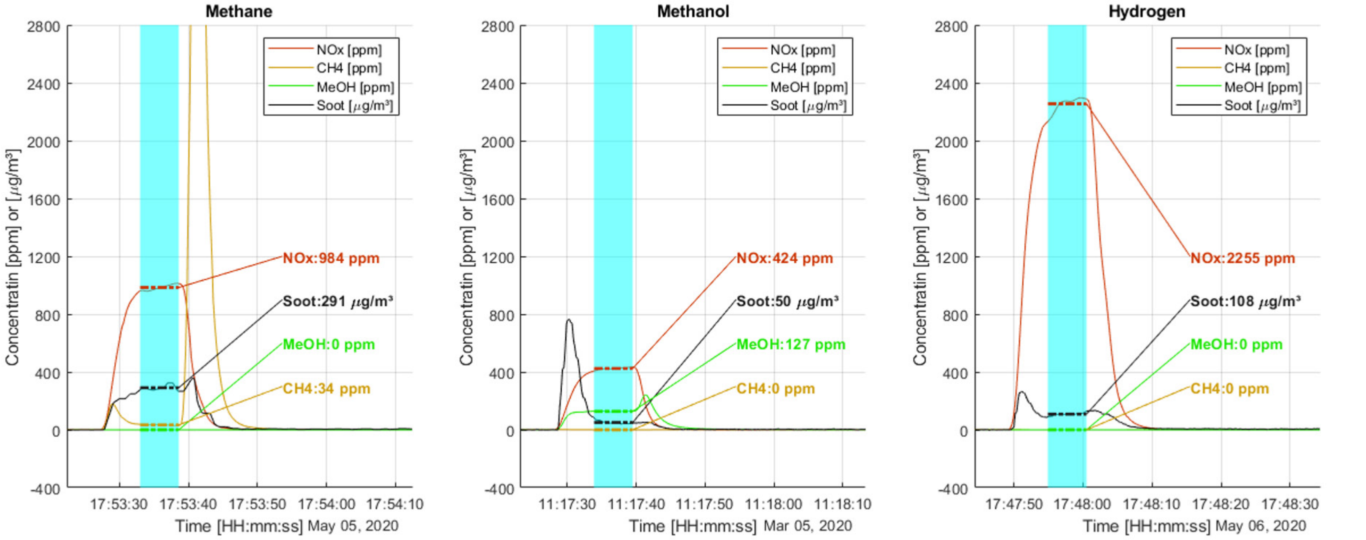

Figure 5 – exhaust emissions resulting from a HPDF combustion process with different main fuels

further course however, unlike with methanol, the flame is visible also in the visible wavelength range. The white flame luminescence corresponds to the broadband (white) light emission which is also reported in literature [14, 15] for hydrogen flames. The same literature sources [15] indicate that the combustion of fuels containing oxygen (such as Ethanol) has a significantly lower light emission compared to hydrogen, which is consistent with observations in the recordings shown here.

In order to get a first estimation of the emissions with the different fuels, the gaseous emissions were measured with an FTIR, and the soot with a photoacoustic sensor (AVL MicroSoot) during optical engine operation. Both devices record data with a sampling rate of 5Hz. For one operating point, the optical engine is fired for 70 cycles (the first 50 cycles are recorded with the cameras). To get rid of sealing oil that has leaked into the injector before the first cycle, the main fuel injection is set to a late crank angle and a very short injection duration for the first cycle and is brought to its target value in terms of injection start and duration in the following 12 cycles. After the 70th cycle, the main fuel injection parameters are automatically set again to the values of the first cycle, in order to prevent damage of the optical engine. Between the first cycles, where larger portions of sealing oil are injected with the main fuel, and the 70th cycle, there is a time slot of 5.6 seconds (~16 cycles) where the emission levels are nearly constant. The recorded values in this time slot are averaged and considered as characteristic emission levels for that experiment.

With methane as fuel in a HPDF combustion process, methane emissions are at a level of ~30ppm, which is much lower than in most of todays lean-burn gas engines. However, there are relevant NOx and soot emissions which have to be treated with an appropriate exhaust aftertreatment system (SCR and possilby also DPF). With methanol, NOx and soot emissions are lower than with methane, but some unburned methanol can be measured in the exhaust. With hydrogen, there are of course no methane or methanol emissions, and soot emissions are also very low. However, due to the high adiabatic flame temperature of hydrogen, NOx emissions are much higher than with methane as fuel.

Summary and Conclusion

With methane, methanol and hydrogen, different fuels, which can be possibly produced in a climate-neutral way by renewable electricity, are tested with a high-pressure dual fuel combustion process in an optical engine with emission level measurement. The results show that this combustion process achieves very stable, mixture-controlled combustion regardless of the properties of the fuel. Similar to diesel combustion, the heat release rate is closely linked to the injection rate, and after end of injection dominated by mixing of fuel and air. Optical recordings can explain phenomena like ignition, soot generation and burn out, and are a very good reference for validation of CFD simulation models. Exhaust emission measurements show that HPDF combustion results in NOx and soot emissions that are higher than in current lean-burn gas engines and have to be addressed with an appropriate aftertreatment system. However, unburned fuel emissions are much lower. Especially in the case of methane this is of great importance, as methane has a very high global warming potential (28 times as high as CO2, on a 100 year basis), and catalytic aftertreatment of methane emissions is still very difficult. Another benefit of the HPDF combustion process is its outstanding tolerance to fuel properties – even hydrogen, which is extremely difficult to handle in premixed gas engines, can be easily burned at an IMEP of 26bar without any risk of preignition or other uncontrolled combustion phenomena.

Acknowledgements

This research was funded by the Federal Ministry of Economics and Technology of Germany within the project MethQuest / MethMare (www.methquest.de). The project was carried out in collaboration with Woodward L'Orange GmbH and MTU Friedrichshafen GmbH. Their support is thankfully acknowledged.

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