2007-01-0474

The effects of blending hydrogen with methane on engine operation, efficiency, and emissions

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ABSTRACT

Hydrogen is considered one of the most promising future energy carriers and transportation fuels. Because of the lack of a hydrogen infrastructure and refueling stations, widespread introduction of vehicles powered by pure hydrogen is not likely in the near future. Blending hydrogen with methane could be one solution. Such blends take advantage of the unique combustion properties of hydrogen and, at the same time, reduce the demand for pure hydrogen. In this paper, the authors analyze the combustion properties of hydrogen/methane blends (5% and 20% methane [by volume] in hydrogen equal to 30% and 65% methane [by mass] in hydrogen) and compare them to those of pure hydrogen as a reference. The study confirms that only minor adjustments in spark timing and injection duration are necessary for an engine calibrated and tuned for operation on pure hydrogen to run on hydrogen/methane blends.

INTRODUCTION

Several national and international organizations consider hydrogen to be the most promising future energy carrier and fuel for mobile applications. In the ideal long-term scenario, hydrogen will be used to power fuel cells that will convert chemical energy into electrical energy and then into mechanical energy by using electric motors.

For this ideal scenario to become a reality, several hurdles have to be overcome, among them the lack of hydrogen infrastructure and appropriate onboard storage devices and the high cost of fuel cells. To begin the transition toward a hydrogen infrastructure and to address some of the issues related to hydrogen, some researchers have proposed using hydrogen to fuel internal combustion engines as a short- to mid-term solution. Several publications on hydrogen-powered engines and vehicles have been generated; U.S. and foreign manufacturers have been conducting ongoing research and development work in this area [1], [2].

Research organizations have also begun blending small amounts of hydrogen with other fuels to improve their combustion properties. The blends have included both liquid and gaseous fuels [3], [4].

This paper focuses on hydrogen/methane blends in a single-cylinder research engine. The combustion behavior, emissions, and performance of the engine fueled with blends of 5% and 20% methane in hydrogen are compared with engine operation on pure hydrogen (used as a baseline). The paper also identifies necessary changes in the engine control unit (ECU) to safely operate the engine on hydrogen/methane blends. The goal of this study is to provide data from the single-cylinder engine that can be used to convert a hydrogen vehicle to run on hydrogen/methane blends.

TEST SETUP

ENGINE TEST CELL AND RESEARCH ENGINE

The engine used to conduct our investigations is an automotive-size, spark-ignited, single-cylinder research engine. The specifications of the engine are summarized in Table 1.

The engine used in the hydrogen vehicle is a supercharged 6.0-L V-8. A good transferability can be expected, although the displacement of the single-cylinder engine is lower than the individual cylinder displacement of the vehicle.

The engine is located in a designated hydrogen engine test cell that features a hydrogen metering and leakage monitoring system, as well as a hydrogen emissions analyzer and standard emissions measurement equipment. A more detailed description of the engine test cell and the engine configuration can be found in [5]. For these tests, the engine was fueled from high-pressure cylinders containing the premixed blends. The actual composition of the blended gases can be found in the Appendix.

Engine manufacturer	Ford Motor Company
Cylinders	1
Displacement (L)	0.5
Bore (mm)	89
Stroke (mm)	79.6
Compression ratio	11.4:1
Valve train	4V dual overhead cam (DOHC)
Maximum torque (Nm)	30
Speed range (RPM)	800–6,000
Injector	(6 bar) Quantum port fuel injection (PFI)

Table 1: Research engine specifications

COMPARISON OF FUEL PROPERTIES

The fuels used in this study are pure hydrogen (100% H_2), a blend of 5% methane in hydrogen (5% CH_4), and a blend of 20% methane in hydrogen (20% CH_4). Although both base components are gaseous under ambient conditions, the specific fuel properties differ quite significantly. As shown in Fig. 1, the lower heating value of pure hydrogen (120 MJ/kg) is more than twice as high as that of pure methane (50 MJ/kg). Because of the large difference in molar mass (see Table 2), the mass-based composition of the blends is considerably different than the volume-based composition.

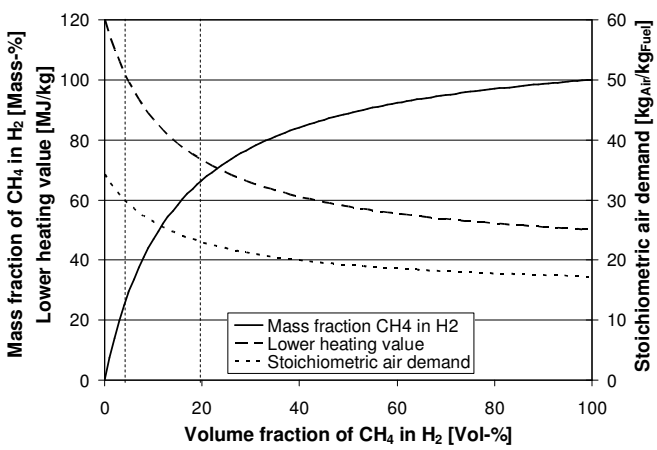

Fig. 1: Influence of composition on fuel properties

In Table 2, the gas properties of the tested blends are compared with those of the base gases.

The fuel properties result in a mixture calorific value (in hydrogen port injection) of about 3.2 MJ/m^3; the calorific value of pure methane is about 3.4 MJ/m^3. So the blended fuels offer a small advantage in terms of power density, although the mixture calorific values are still significantly lower than those of gasoline or diesel (~3.8 MJ/m^3) [6].

Parameter	Unit	H_2	5% CH_4	20% CH_4	CH_4
Density	kg/m^3	0.089	0.12	0.22	0.72
Molar mass	kg/ kmol	2.016	2.72	4.82	16.04
Lower heating value	kJ/kg	120,000	99,339	73,419	50,000
Stoichio-metric air demand	kg_{air}/ kg_{fuel}	34.3	29.3	22.9	17.2
Laminar flame speed	cm/s	200	n.a.	n.a.	40

Table 2: Properties of base gases and blends

TEST PROGRAM

Due to calibration simplicity, the operating strategy currently implemented in most hydrogen-powered vehicles is a lean-burn strategy at a constant air/fuel ratio utilizing a throttle. In order to keep the nitrogen oxides (NO_x) emissions low, the relative air/fuel ratio is usually set to $\lambda \geq 2$. However this operating strategy ($\lambda \geq 2$) results in a significant loss in power output. For this reason, supercharging is commonly used to restore power density, particularly on the vehicle used for these tests.

Nevertheless, the wide ignition limits of hydrogen allow the engine to run unthrottled across a wide operating range. In order to assess the combustion properties of the blends compared with those of pure hydrogen, all operating points on the single-cylinder research engine were run unthrottled. The three different fuels were tested at two engine speeds (2,000 RPM and 4,000 RPM). For each speed, spark sweeps were performed at several load points in order to identify maximum brake torque (MBT) spark timing.

Because the results at speeds of 2,000 and 4,000 RPM show identical trends, the data presented below are concentrated on selected operating points at a speed of 2,000 RPM.

RESULTS AND ANALYSIS

ENGINE EFFICIENCY AND COMBUSTION BEHAVIOR

In Fig. 2 the indicated efficiencies for engine loads of approximately 2, 4, and 6 bar indicated mean effective pressure (IMEP) are plotted versus spark timing at an engine speed of 2,000 RPM. Solid black lines represent pure hydrogen, dotted dark grey lines represent a blend of 5% methane in hydrogen, and dotted and dashed light grey lines represent a blend of 20% methane in hydrogen. Because all operating points were taken in an unthrottled condition, higher engine loads result in more fuel-rich mixtures. The flame speed for those gases is highly dependent on the air/fuel ratio, with a maximum close to stoichiometric. Thus, higher engine loads result in faster combustion speeds and therefore require less spark advance. Furthermore, the flame speed for hydrogen is very high compared with those for other

fuels [7]. In a stoichiometric mixture, the laminar flame speed of hydrogen is five times faster than that of methane (see Table 2). In order to compensate for the lower combustion speed with increased methane in the blend, the MBT spark timing occurs earlier for the 20% blend compared with the 5% blend or pure hydrogen.

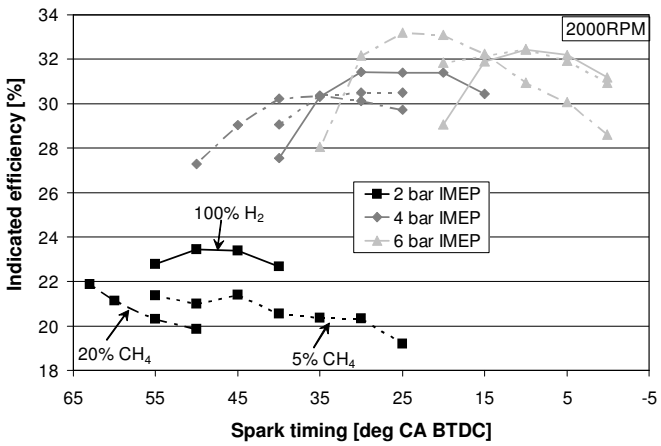

Fig. 2: Indicated efficiency versus spark timing at a speed of 2,000 RPM

The MBT spark timing for the operating points shown in Fig. 2 is summarized in Table 3. Compared with pure hydrogen, the 5% methane mixture requires approximately 5 degCA spark advance; the 20% methane mixture requires approximately 15 degCA.

The actual peak efficiencies for the different fuels are in a comparable range. For low engine loads, pure hydrogen operation results in higher efficiencies compared with the blends. This is, again, because the combustion speed of these lean mixtures is fairly low for the methane blends. For high engine loads, the blended fuels achieve higher efficiencies than pure hydrogen. The extremely short combustion duration for close-to-stoichiometric pure hydrogen operation results in high combustion temperatures and, thus, increased wall heat losses [8].

	H_2	5% CH_4	20% CH_4
2 bar	45 – 50	55	63+
4 bar	25	30	35 – 40
6 bar	10	10 – 15	20 – 25

Table 3: MBT spark timing as a function of IMEP and fuel composition at 2,000 RPM

We performed a detailed analysis of the combustion behavior in order to evaluate the influence of blending different concentrations of methane and hydrogen. On the basis of high-speed cylinder pressure measurements, we calculated the rate of heat release. Fig. 3 shows the pressure traces, as well as the rates of heat release for a medium-load point (4 bar IMEP) at a speed of 2,000 RPM. The spark timing was set for maximum brake torque. The air/fuel ratio λ for these operating points is between 2.5 for the 20% methane blend and 2.8 for pure hydrogen. The difference in air/fuel ratio results from the slightly lower efficiency in blended operation (see Fig. 2). Although the mixture is leaner in pure hydrogen operation, the combustion duration is still shorter for pure hydrogen than for the two blends. The maximum value of heat release is comparable for the three fuels.

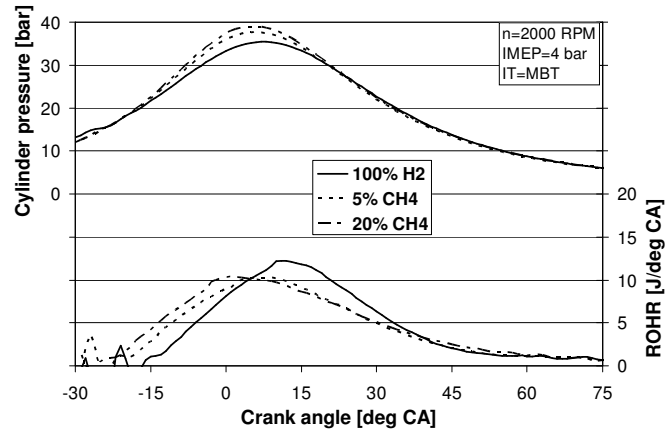

Fig. 3: Pressure traces and rates of heat release at medium load (2,000 RPM, 4 bar IMEP)

The difference in combustion behavior and flame speed between the pure hydrogen and the blends is even more distinct at higher engine loads resulting from richer mixtures. Fig. 4 compares pressure traces and heat release rates for an IMEP of about 6 bar, which corresponds to an air/fuel ratio λ of approximately 1.7. To clearly see the combustion properties, the spark timing was held constant at 10 degCA before top dead center (BTDC). In pure hydrogen operation, combustion takes only about 25 degCA, which is remarkable considering that it is still a lean mixture. In comparison, the combustion duration for the 5% methane blend is about 35 degCA; the combustion duration for the 20% methane blend is significantly longer – about 55 degCA. In addition, the maximum rate of heat release is significantly higher for pure hydrogen operation, which also results in a higher combustion peak pressure (45 bar for pure hydrogen compared with about 30 bar for the 20% methane blend).

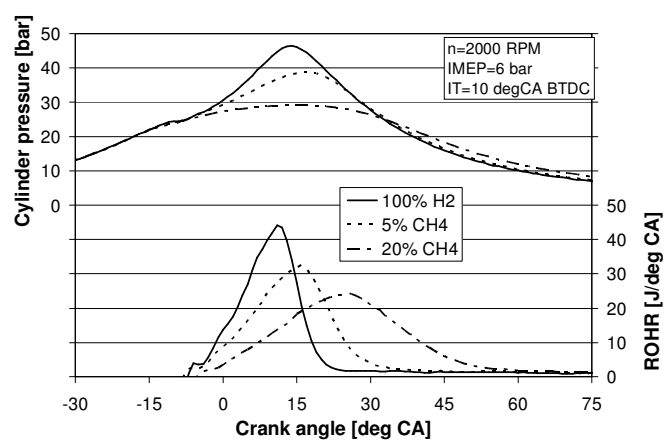

Fig. 4: Pressure traces and rates of heat release at high load (2,000 RPM, 6 bar IMEP)

Overall these results show that, to achieve maximum efficiency, the spark timing has to be advanced in blended operation compared with pure hydrogen operation. For the 5%-methane-in-hydrogen blend, the spark advance is only minor and does not significantly reduce engine performance. For the 20%-methane blend, spark timing definitely needs to be adjusted for optimal results.

INFLUENCE OF BLENDING ON FUEL MAPS

Because of the lower heating values of the blends compared with that of pure hydrogen, the mass of fuel that must be injected to reach the same engine load increases with an increased amount of methane in the blend. On the other hand, because the density of methane is higher than that of hydrogen, the density of the hydrogen/methane blends increases with an increased proportion of methane in the blend. Although the mass almost doubles when a 20% methane blend is injected instead of pure hydrogen, the injection duration remains almost unchanged (see Fig. 5).

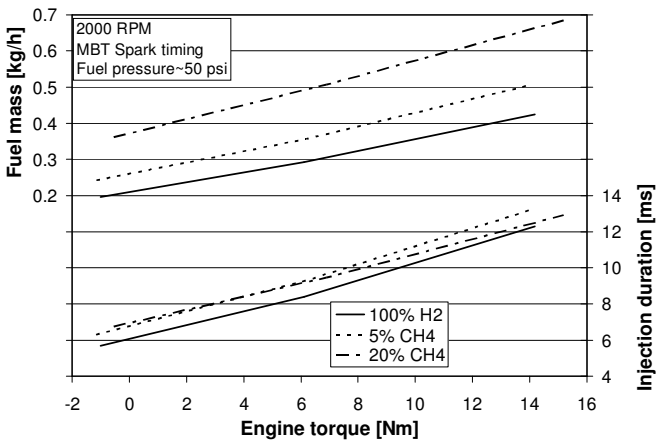

Fig. 5: Influence of fuel composition on injected fuel mass and injection duration

Given identical injector flow characteristics and an isentropic critical injection event, the energy flow per unit area can be calculated as

$$\overline{E} = \frac{\dot{E}}{A} = LHV \times \rho \times \sqrt{\kappa \times R \times T} \qquad (1)$$

where:

$\overline{E}$ .....Energy flow per unit area [W/m^2]

$\dot{E}$ .....Energy flow [J/s]

A .....Flow area [m^2]

LHV .....Lower heating value [J/kg]

ρ .....Density [kg/m^3]

κ .....Isentropic exponent [-]

R .....Gas constant [J/kgK]

T .....Temperature [K]

Fig. 6 shows the trace of absolute energy flow per unit area versus concentration in the blend. The figure also shows the relative flow compared with that of pure hydrogen. Starting from pure hydrogen, the energy flow slightly decreases, with a minimum relative flow of about 95% at a concentration of about 15% methane in hydrogen. For methane-rich blends (>50% methane in hydrogen), the energy flow rises significantly. Overall, the influence of the energy flow in the area of interest for these investigations (0–20% methane in hydrogen) is minimal.

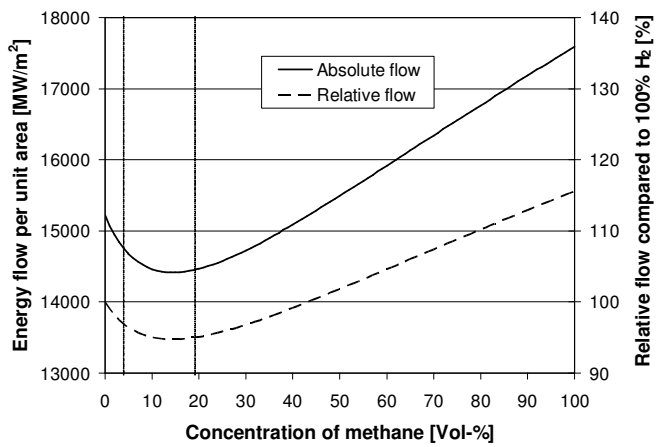

Fig. 6: Energy flow versus methane concentration

EMISSIONS BEHAVIOR

The only relevant emissions in hydrogen operation are NO_x emissions, which are highly dependent on the combustion temperature and, subsequently, on the air/fuel ratio. In premixed operation with air/fuel ratios λ higher than 2, the NO_x emissions are negligible. For richer mixtures, a distinct NO_x emissions peak can be observed at an air/fuel ratio of λ~1.3. A further reduction in air/fuel ratio toward stoichiometric operation results in a decrease in NO_x emissions [9].

As shown in Fig. 7, an increase in load results in an increase in NO_x emissions. Because of the lean-operating strategy, only a negligible amount of NO_x emissions occurs at an engine load of 2 bar IMEP. At a medium engine load (4 bar IMEP), the NO_x emissions are generally still below 10 ppm. Only operating points with extremely early spark timing (resulting in high combustion temperatures) produce NO_x emissions up to 100 ppm. At a higher engine load (6 bar IMEP), the NO_x emissions increase significantly (note the logarithmic scale). The same trend – with an increase in NO_x emissions for early spark timing – can be seen. Because of the faster combustion (and thus higher combustion temperatures) of pure hydrogen compared with the blends, in particular at high engine loads, the NO_x emissions are higher for pure hydrogen operation.

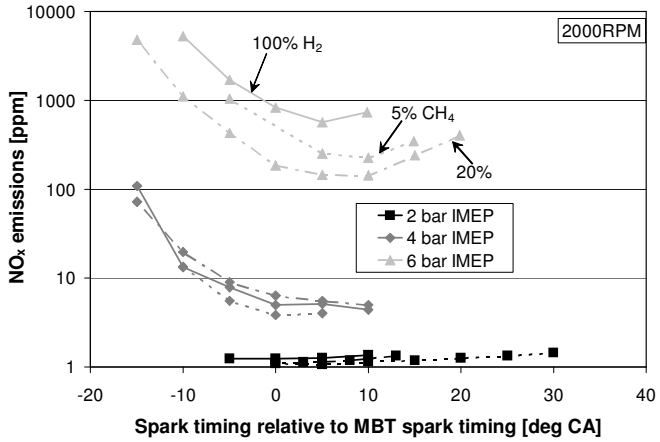

Fig. 7: Influence of blending on NO_x emissions

Hydrogen emissions are not regulated by any standards, but it is nevertheless important to monitor and minimize these emissions because they directly affect engine efficiency. Fig. 8 shows the hydrogen emissions associated with pure hydrogen operation and operation using the two hydrogen/methane blends. Very lean engine operation (IMEP of ~2 bar) results in a very slow combustion rate and, thus, a higher portion of unburned fuel. This trend can be seen for all three fuels. Because of the even lower combustion speed with an increased amount of methane in the blend, this effect is even more significant. With increased engine load, the hydrogen emissions drop well below 2,000 ppm. Considering that up to 30% (by volume) of the initial fuel gas mixture is hydrogen, 2,000 ppm (0.2% by volume) is minimal and represents an almost negligible loss in efficiency [10].

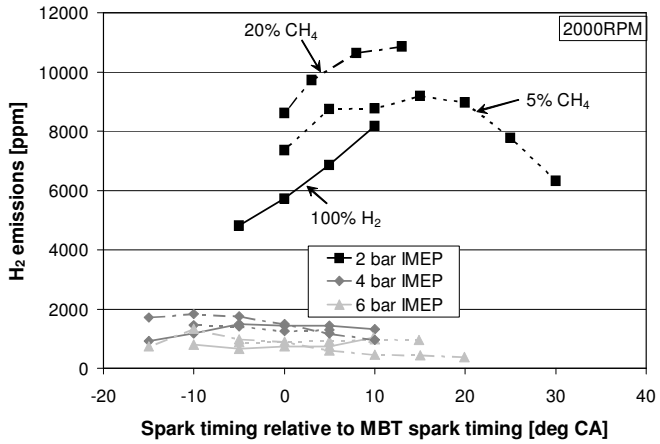

Fig. 8: Influence of blending on hydrogen emissions

The second component of the blended fuels, methane, was also monitored during engine operation. The trends for methane emissions are very similar to those for hydrogen emissions. Because the fuels contain different amounts of (or no) methane, the absolute levels of the methane emissions differ significantly (see Fig. 9). As expected, methane emissions during pure hydrogen operation are close to zero.

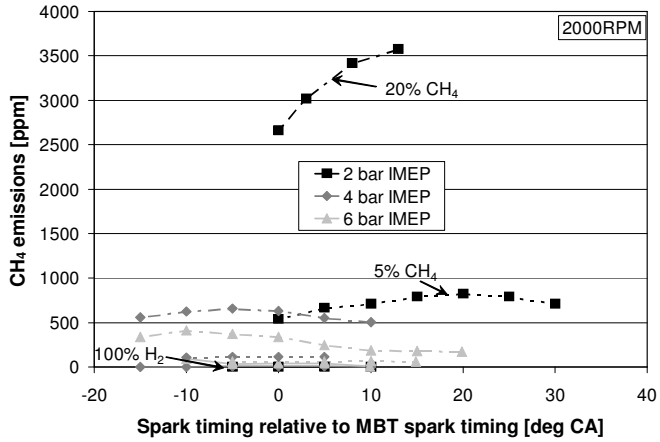

Fig. 9: Influence of blending on methane emissions

Given that the engine is fueled with a homogenous mixture of hydrogen, methane, and air, we would expect that the ratio of unburned fuel (methane and hydrogen) should be the same as the hydrogen/methane ratio of the feed fuel. Fig. 10 shows the ratio of methane to hydrogen emissions for the two different blends.

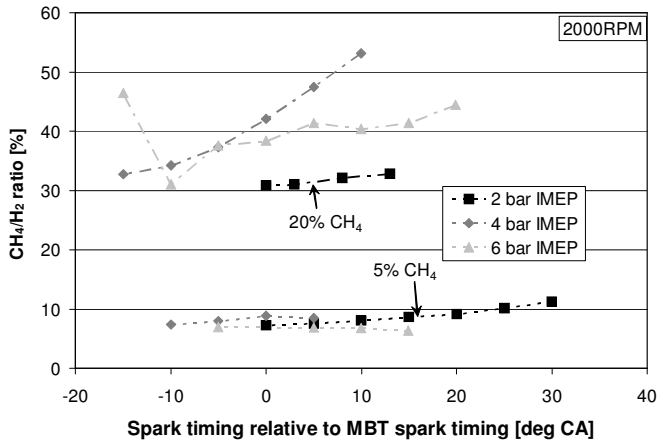

Fig. 10: Traces of methane/hydrogen emissions ratio

For the 5% methane mixture, the ratio of methane to hydrogen emissions is fairly constant, with an average of about 8% and a maximum of 11%. On the other hand, the methane-to-hydrogen emissions ratio for the 20% methane blend varies quite significantly, with a minimum ratio of over 30% and a maximum of nearly 55%. The average ratio of methane to hydrogen emissions for the 20% blend is almost 40%. In addition, the ratio increases with retarded spark timing – an effect that can also be seen for the low load traces of the 5% methane blend. This finding indicates that, toward the end of the combustion process in areas near the combustion chamber walls, hydrogen is still able to burn, while the local conditions do not allow methane to burn anymore. This effect is very likely caused by the shorter quenching distance of hydrogen (0.6 mm*) compared with that of methane (2 mm*) [8].

* Values are for ambient conditions (1.013 bar, 20°C) and a stoichiometric mixture.

INFLUENCE OF BLENDING HYDROGEN AND METHANE ON ENGINE CALIBRATION

The main goal of our investigation was to determine the necessary changes and adaptations in the engine control unit (ECU) of a hydrogen-powered vehicle in order to operate it on blends of hydrogen and methane. Currently, the truck is operated with a lean-burn strategy with a constant air/fuel ratio and thus avoids NO_x-critical operating regimes. The vehicle uses a belt-driven supercharger to compensate for the loss in power output associated with hydrogen port injection operation. Further information on the truck and the operating strategy can be found in Reference [11].

INJECTION

In order to avoid operating regimes with high NO_x emissions, the truck is run on a lean-burn strategy with a constant relative air/fuel ratio λ. The calibration of the ECU was performed for a relative air/fuel ratio of λ~2.25. Because of the changes in energy flow, adjustments in injection timing will be necessary. If only discrete blends with known compositions are being used, the injection settings can be changed manually according to the dependencies shown in Fig. 6. If various blends or blends with unknown compositions are used to fuel the vehicle, the above-mentioned curve should be implemented in the ECU and a means to identify the composition of the mixture should be developed.

IGNITION

Because of the lower combustion speed of methane compared with that of hydrogen, the spark timing has to be adjusted for optimum engine performance. With the current engine control strategy, the engine is being run with a constant air/fuel ratio of λ~2.25. In this air/fuel ratio range, the MBT spark timing with the 5% methane-in-hydrogen blend is about 5 degCA – earlier than with pure hydrogen. For the 20% methane-in-hydrogen blend, the spark timing should be about 15 to 20 degCA – again, earlier than with pure hydrogen. For blends with small amounts of methane (<5% by volume), the engine can be operated without adjusting the spark timing, which will result in only a negligible loss in engine efficiency. For blends with greater amounts of methane, the spark timing should be adjusted to maintain efficiency.

OTHER ECU FUNCTIONS

Although the advanced spark timing that is required when blending hydrogen with methane could lead to knocking, this seem unlikely – both because of the good knocking properties of methane and because the lean-burn strategy itself also inhibits knocking. Moreover, a knock sensor could be used to prevent engine knocking.

Because of the changed composition of the feed fuel, the dependence of the air/fuel ratio on the exhaust oxygen feedback changes slightly. Fig. 11 shows the dependence of exhaust oxygen content and relative air/fuel ratio in the relevant air/fuel ratio regime $1.8 < \lambda < 2.6$. As the figure shows, the feedback of exhaust oxygen content (e.g., ~10% by volume) is equal to an air/fuel ratio λ of 2.1 in pure hydrogen operation. The same oxygen content results in a relative air/fuel ratio of 2.08 with the 5% blend and about 2.05 with the 20% blend.

Knowing that the air/fuel ratio, especially in the region of λ~2, has a crucial influence on NO_x emissions behavior, the effect described above should be taken into account. On the other hand, Fig. 7 shows that blending hydrogen with methane slightly reduces NO_x emissions because of the slower combustion speed of methane compared with that of hydrogen.

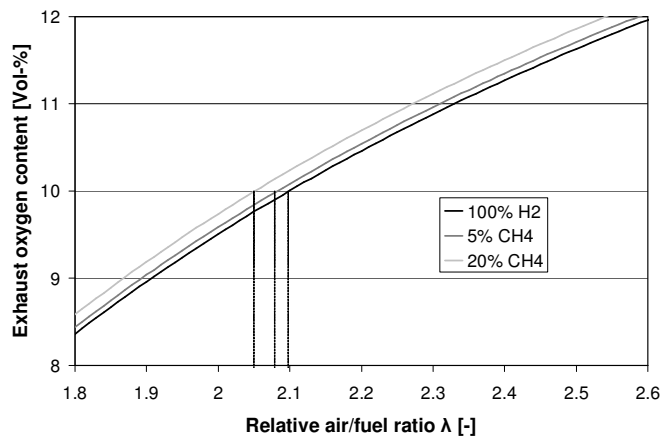

Fig. 11: Relative air/fuel ratio as a function of exhaust oxygen content

CONCLUSION

In order to investigate the effects of blending hydrogen with methane on engine performance, we conducted several tests on a single-cylinder research engine. The goal of these tests was to identify the changes to the engine ECU that are necessary to run the engine on hydrogen/methane blends. On the basis of our results, we can draw the following conclusions.

- Because of the lower combustion speed of methane compared with hydrogen, the spark timing must be advanced with increased amounts of methane in the blend.
- The different properties of methane and hydrogen necessitate adjustment of the injection duration in order to achieve the same engine load (Fig. 6) presents a curve showing the necessary adjustments).
- The NO_x emissions behavior of pure hydrogen compared with hydrogen/methane blends shows the same trends. Because of methane's slower combustion speed, the absolute level of emissions is slightly lower with an increased amount of methane.

- The amount of unburned methane compared with hydrogen in the exhaust is higher relative to the composition of the feed fuel, probably because hydrogen has a shorter quenching distance than methane, allowing for more complete combustion close to the combustion chamber walls.

Overall, the results from the study indicate that only minor adjustments are necessary for an engine calibrated and tuned for operation on pure hydrogen to run on hydrogen/methane blends.

ACKNOWLEDGMENTS

The submitted manuscript was developed by the UChicago Argonne LLC as Operator of Argonne National Laboratory under Contract No. DE-AC-02-06CH11357 with the U.S. Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

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ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
BTDC	before top dead center
CH_4	methane
DOHC	dual overhead cam
ECU	engine control unit
H_2	hydrogen
IMEP	indicated mean effective pressure
MBT	maximum brake torque
NO_x	nitrogen oxides
PFI	port fuel injection
ROHR	Rate of heat release
RPM	rotations per minute
SAE	Society of Automotive Engineers

APPENDIX

REQUESTED VERSUS ACTUAL GAS COMPOSITION

Blend	Unit	5% blend	20% blend
CH_4 requested	vol.-%	5	20
CH_4 actual	vol.-%	4.887	19.77
CH_4 requested	mass-%	29.52	66.54
CH_4 actual	mass-%	29.02	66.22