HYDROGEN CONTAINING GASEOUS BLENDS AS VEHICLE FUELS

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SHRNUTÍ

Článek se zabývá vlivem přítomnosti vodíku v plynném palivu s vysokým obsahem metanu. Dopad složení paliva na pracovní oběh motoru a na jeho parametry je popsán na základě experimentálně zjištěného chování testovacího motoru. Použitá experimentální data byla naměřena při středním zatížení motoru, kdy se neuplatňují žádná omezení z hlediska mechanického a teplotního namáhání dílů motoru. Posuzuje se použitelnost plynných směsí s (vysokým) obsahem vodíku jako paliva pro konvenční plynové motory s atmosférickým plněním.

Konstatuje se, že použití paliva s vysokým obsahem vodíku v konvenčních plynových motorech je možné, i když primárně se předpokládá využití těchto plynných směsí pro budoucí generaci plynových vozidel speciálně pro použití tohoto paliva přizpůsobených.

KLÍČOVÁ SLOVA: ALTERNATIVNÍ PALIVA, VODÍK, ZEMNÍ PLYN, HYTHANE

ABSTRACT

The article describes the influence of presence of hydrogen in a mixture with methane-based gaseous fuels. The impact of the fuel composition on an engine working cycle and on engine-out exhaust properties is described on the basis of experimentally determined engine performances. The experimental data acquired in rather moderate operating conditions are used for determination of basic changes in engine behavior unrestricted by any constraints. The usability of hydrogen-containing fuel blends as a fuel for conventional gas fueled vehicles equipped with naturally aspirated engines is assessed.

The paper concludes that (with respect to engine behavior) the use of hydrogen-containing fuel for existing vehicles is possible even if it is primarily intended for exploitation in a new generation of gas fueled vehicles.

KEYWORDS: ALTERNATIVE FUELS, HYDROGEN, NATURAL GAS, HYTHANE

1. INTRODUCTION

During the introduction of any non-conventional vehicle fuel the well-known chicken and egg syndrome has to be addressed. Insufficient or completely absent refueling infrastructure discourages the potential end user from exploitation any newly introduced fuel, whilst a small number of vehicles in operation does not provide sufficient incentive for building up a refueling network.

There are several possible approaches to ensure proper timing of the simultaneous development of a vehicle fleet along with the refueling infrastructure.

Purposely created communities which combine production and distribution of a newly introduced fuel with its multipurpose exploitation concentrated in a given geographic locality is one possible approach. Introduction of a new transportation fuel in this case can be targeted at the vehicle segment and its exploitation mode so that the fuel advantages are accentuated, whereas disadvantages are suppressed as much as possible.

Direct or indirect support of a desirable development trend in the fuel market by funding a pilot project or by modification of taxation policy is also possible, and can sometimes be successful. The pure engineering way to promote expansion of a suitable range of vehicle fuels is by ensuring engine fuel flexibility. A bi-fuel arrangement enables the vehicle user to benefit from exploitation of an alternative fuel where a refueling infrastructure is available. Vehicle operation outside the range of alternative refueling stations is ensured using a conventional fuel. Two complete fuelling systems have to be installed in a bi-fuel vehicle including two separate fuel tanks. The engine design has to be tailored to cope with the fuel of the worst quality. Effective exploitation of the advantages of any better fuel is only possible by modification of the engine control algorithms. Introduction of blended fuels containing basic (conventional) fuel with the addition of a small amount of a newly introduced

FIGURE 1: Basic arrangement of the testing engine. WG-controlled turbocharger governed by pressure cell.

OBRÁZEK 1: Základní uspořádání zkušebního motoru. Řízení turbodmychadla obtokem spalin je ovládáno přetlakovou dózou.

FIGURE 2: Current arrangement of the testing engine – VTG-controlled turbocharger governed by Smart Remote Actuator, low pressure EGR line equipped with oversized coolers.

OBRÁZEK 2: Stávající uspořádání zkušebního motoru – Turbodmychadlo s variabilní geometrií turbíny je ovládáno elektronicky řízeným vybavovačem, vedení nízkotlakové recirkulace spalin je opatřeno mohutně dimenzovanými chladiči.

fuel is another possible way for phased transition from fossil fuels towards the use of renewable and environmentally friendly ones. The presence of a small amount of FAME in commonly distributed diesel fuel is an example of this strategy in practice.

A similar strategy has been proposed for smoothing the transition from gaseous hydrocarbons of fossil origin to (future) pure hydrogen fuelling. It is suggested that hydrogen will be mixed with methane based fuels (or pure methane) and delivered into the vehicle fuel tank as a component of a blended fuel. The whole fuelling system has to be able to operate on either the base fuel or with a fuel blend with a certain content of hydrogen.

There are certain implicit advantages to the use of hydrogen as a vehicle fuel.

It is totally renewable assuming that a sufficient amount of energy for hydrogen production is available. During the combustion process itself, it does not produce any carbon-containing component.

On the other hand, there are significant disadvantages. The fuel calorific value is rather low, which significantly restricts the vehicle range. The mixture calorific value is also lower than that for gaseous hydrocarbon fuels, which worsens the conditions for achieving a high specific power of the engine. Moreover, the knock resistance of hydrogen is considered to be low. Numerical evaluation of knock resistance of gaseous fuels by methane number indicates that hydrogen is the most knock promoting.

The article deals with a description of the impact of hydrogen presence in a fuel blend on the behavior of the engine working cycle, and its effect on engine-out exhaust parameters. The description is based on results experimentally acquired at the author's engine laboratory.

2. TEST EQUIPMENT AND PROCEDURES

A 4×Ø102/120 engine was dedicated as the task carrier. It was rebuilt from a diesel engine by lowering the compression ratio to CR=12, replacing the injectors with spark plugs and adding a gas fuelling system and corresponding accessories. The robust engine design enables operation under rough conditions, especially when medium or even high levels of knock occur.

The original arrangement of the test engine (without complex accessories that would hide it from view) is shown in Figure 1. Subsequently the engine accessories were modified by replacing the WG-controlled turbocharger for one having variable turbine geometry, and others such as the EGR line. The current state of the test engine is shown in Figure 2.

The engine is equipped with a distributed control system enabling independent adjustment of mixture throttle position, ignition timing, EGR throttle position and VTG rack position. Mixture composition can be adjusted either manually to any desired value or by closed loop λ -control to air excess of $\lambda = 1$. Metering of base fuel delivery and mixture formation is performed by a central mixer. Two additional gaseous components can be delivered during engine running directly into the engine intake manifold upstream of the compressor.

FIGURE 3: On-line formation of fuel blends.

OBRAZĚK 3: Princip a zařízení pro realizaci změny složení paliva za chodu motoru.

In this way the fuel blend composition can be adjusted within a certain range and even changed continuously while the engine is running.

Metering of the fuel additives is performed by mass flow meters as shown schematically in Figure 3.

The engine was coupled to a DC dynamometer.

Pressures and temperatures of the working substance were measured in various parts of the engine manifolds. Flows of fuel(s) and air, cooling water temperature in both engine and EGR cooling systems, engine speed and torque were sensed and recorded. Moreover, feedback messages from all actuators (mixture throttle, EGR control valve, fuel metering orifice, ignition timing adjustment and VGT rack position) were also acquired. Exhaust gas composition was determined using a conventional set of gas analyzers. An additional set of gas analyzers sensed the mixture composition taking the sample from the engine intake manifold. The analyzer outputs were used as computational inputs for the determination of the EGR rate and/or for verification of the fuel blend composition.

During the whole experimental run the angle-resolved patterns of in-cylinder pressures and the absolute pressures in both the intake and the exhaust manifold (sensors installed as close to the cylinder as possible) were acquired. Simultaneously with the record of angle-resolved fast-changing pressure patterns, the instantaneous crankshaft speed was measured in order to determine cylinder-to-cylinder variation and verify the "single cylinder" acquired pressure patterns representative enough for the whole engine.

Knock occurrence and intensity was monitored using an AKR® device. This device elaborates the signal from a conventional vibration sensor (so called knock sensor) by application of Discrete Fourier Transform using a Digital Signal Processor (DSP) HW platform. It generates an analog output signal which can be used for ignition timing control. At the author's laboratory

FIGURE 4: Full load curve proposal.

OBRAZĚK 4: Návrh vnější rychlostní charakteristiky zkušebního motoru.

this AKR output was only sensed by a data acquisition system. Knock intensity was recorded in this manner including the time-dependent plot of the (well-known) self-exciting nature of the knock phenomena when knock was not suppressed by any control intervention.

Natural Gas (NG) was used as the basic fuel. Its rated composition is listed in Table 1 as it was determined by compilation of information from open sources (especially from information published by the main Czech NG grid operator (CaP).

TABLE 1: Properties of Natural Gas

TABULKA 1: Vlastnosti zemního plynu

Fuel Composition %(vol)	
CH ₄	98.39
N ₂	0.84
C ₂ H ₆	0.44
C ₃ H ₈	0.16
C ₄ H ₁₀	0.1
CO ₂	0.07
Fuel Properties	
Hinf [MJ/m ³] (Fuel CV)	35.79642
Hinf [MJ/kg] (Fuel CV)	49.17224
Fuel density [kg/m ³]	0.72798
Wobbe_Index [MJ/m ³]	47.69263
O _{t0,2} [mol/mol]	1.99815
LtAir [kg/kg]	16.93385
Mixture Properties	
Hinf _{Mx} [MJ/m ³] (Mixture CV)	3.396397
Hinf _{Mx} [MJ/kg] (Mixture CV)	2.741867
Mixture density [kg/m ³]	1.238702

Proposed patterns of the engine full load curve are shown in Figure 4.

3. PROPERTIES OF AN ENGINE OPERATING WITH HYDROGEN-CONTAINING FUEL GAS

The experimental equipment is set up to investigate the influence of fuel composition variations under the conditions of high specific power. However, in this article the findings are presented enabling judgment of the basic properties of hydrogen-containing fuels used under the conditions found in the case of a naturally aspirated engine. In this way we are able to assess the usability of hydrogen-containing fuels in modern gas fueled vehicles which are powered by a naturally aspirated engine either being arranged as bi-fuel (petrol/gas) or derived from naturally aspirated petrol fueled engines, or implemented using simplest form of cost effective accessory layout. Simultaneously, the pure influence of the fuel composition is described in a way that is not clouded by implementation of sophisticated control interventions, as they are intended for use in the future generation of mono-fuel uncompromisingly optimized engines/vehicles.

During the experiments whose results are presented later, the mixture throttle was adjusted to the position giving a BMEP value approx. at the level of WOT operation of a naturally aspirated engine. Closed loop λ -control was kept active during the measurements; therefore, all presented results were recorded at stoichiometric operation. The results acquired at an engine speed of 1800 rpm are presented.

The basic influence of hydrogen presence in the fuel blend is illustrated in Figure 5 and Figure 6. These figures describe the engine working cycle properties for pure NG operation as well as with approx. 26% (by volume) of hydrogen in a mixture with NG. Ignition timing was adjusted to the same value for both fuels (namely 19° BTDC = the optimum for pure NG operation). The figures illustrate the typical impact of the presence of hydrogen in fuel – increase of the burning velocity. The peak cycle pressure increases, and it is shifted closer to TDC. In-cylinder temperature pattern behaves correspondingly. The patterns in Figure 6 directly describe the phenomenon of increased burning rate.

Figure 7 summarizes the results of indicator diagram evaluation for various hydrogen contents in the fuel blend. The experimental data were acquired exploiting the ability of on-line formation of the fuel blends of various compositions as described in the comment to Figure 3. The angle-resolved patterns in Figure 5 and Figure 6 belong to both endpoints of the curves in Figure 7. The hydrogen content (horizontal axis) of the fuel is expressed as a volumetric fraction of hydrogen in its mixture with NG. The plot of heat release is shown in Figure 7 using curves of the angle position in which heat release reaches a certain value

FIGURE 5: In-cylinder pressure and temperature patterns – Medium speed / medium load.

OBRAZEK 5: Průběh tlaku a teploty ve válci – Střední zatížení a otáčky.

FIGURE 6: Cumulative Heat Release and Rate-of-Heat-Release patterns – Medium speed / medium load.

OBRAZEK 6: Průběh integrálního vývinu tepla a jeho derivace – Střední zatížení a otáčky.

FIGURE 7: Indicator diagram evaluation results.

OBRAZEK 7: Výsledky vyhodnocení indikátorového diagramu.

FIGURE 8: Engine power and efficiency.

OBRÁZEK 8: Energetické parametry.

FIGURE 9: Exhaust gas composition.

OBRÁZEK 9: Složení výfukových plynů.

FIGURE 10: Miscellaneous performances.

OBRÁZEK 10: Další relevantní parametry.

(CAxx where xx is normalized cumulative heat release in %). The isolines CAxx are approximately equidistant and therefore the increased amount of hydrogen in fuel mainly shortens ignition delay.

Engine-out parameters are presented in the subsequent figures. In Figure 8 the engine power is expressed by curves of brake and indicated mean effective pressures. The effectiveness of energy exploitation delivered by the fuel is expressed in terms of brake specific heat consumption. In order to give a more complete insight, the exhaust temperature (measured upstream of the turbine inlet) is also displayed in this figure. Engine efficiency remains almost unchanged while engine power decreases with increased hydrogen content in the fuel primarily due to the decreased calorific value of the mixture. The change of engine power is visible but not crucial.

The composition of raw (engine-out) exhaust gas is expressed in Figure 9 in terms of molar fractions of relevant components in a dry sample. The remarkable decrease of CO_2 content corresponds to the decreased content of carbon in the fuel. The decrease of molar fractions of products of incomplete oxidation (both CO and CH_4) indicates improved chemical efficiency of the combustion process. The increase of NO emissions is excited by the higher temperature level during the entire high pressure part of the engine working cycle.

A set of less common parameters is presented in Figure 10. The quite conventional parameter of specific emissions of carbon dioxide (mCO_{2r}) is determined from measured data. It expresses the decrease of CO_2 emissions more representatively than the mere presentation of CO_2 content in exhaust gas (as shown in Figure 9). To provide a more complete insight into the CO_2 issue, the curve of theoretical specific CO_2 emissions is displayed in Figure 10. It is calculated from a mass balance equation using inflow of fuel-contained carbon as the calculation input. It emulates the tailpipe emission of CO_2 assuming 100% efficiency of the conversion of the products of incomplete oxidation as part of exhaust gas after treatment. The mCO_{2t} value describes the tendency of a particular fuel to create GHG in an absolute manner (independent of engine behavior). Both curves of specific emissions of carbon dioxides show almost the same slopes. The value SumGWP20 is compiled as a sum of specific emissions of CO_2 and specific emissions of methane multiplied by its global warming potential (namely 72 as mentioned for a time horizon of 20 years). It can be seen that the curve of SumGWP20 descends more steeply than the curves of specific emissions of CO_2 themselves. Therefore, the rising amount of hydrogen in the fuel blend not only reduces the global warming index by decreasing the presence of carbon in the reactants of the oxidation reaction, but also minimizes the content of unburned methane in engine-out exhaust. The high

reaction rate of hydrogen oxidization probably minimizes the volume of the quenching zones. Of course, this positive effect will be attenuated as soon as the tailpipe emissions are considered. Nevertheless, it is not negligible taking into account the generally expected problem with additional oxidization of methane in a catalytic converter. The specific emission of methane itself evaluated from raw exhaust gas composition is also presented in Figure 10.

The parameter Vehicle Range (VRng in Figure 10) was derived and defined (in the author's institute) for a numerical expression of the ability of the particular vehicle fuel regarding the effectiveness of its on-board storage. It is defined as a product of fuel CV (by volume) and engine efficiency. In short, the value of VRng determines the amount of useful energy (at engine flywheel) per nm^3 of stored fuel. The steeply descending slope of VRng highlights the main disadvantage of the use of hydrogen as a vehicle fuel.

4. CONCLUSIONS

As already mentioned, the article is focused on the assessment of mixtures of methane-based fuels with hydrogen when intended for use as fuels for conventional (i.e. naturally aspirated) vehicle engines.

Similar curves to that presented in Figure 7 to Figure 10 were obtained from engine operation at various speeds. Then the presented pattern can be considered to be typical and conclusions can be derived.

Certain partial conclusions were mentioned in the comments to the figures. In addition it is worth mentioning that no knock was observed during the experiments whose results are covered in this article, or in any other experiments in which engine load was kept at the level typical for WOT operation of a naturally aspirated engine.

The generalized results are illustrated in Figure 11. In this figure the fuel features derived merely from fuel composition are compared with experimentally obtained results. In order to enable plotting on a common vertical axis, the values are presented as relative values while pure NG is considered to be a reference state.

The ability of the fuel for effective on-board storage is given in principle by its CV (by volume – the CV_FI value in Figure 11). The comparison with the VRng curve (which regards the associated changes in engine efficiency) shows only very subtle differences.

Similarly, the main fuel feature influencing engine power output is mixture CV (per unit of mixture normal volume – CV_Mx in Figure 11). In Figure 11 the mixture CV is compared with the actually recorded BMEP value. Again, the difference (caused by engine efficiency changes) is very subtle.

FIGURE 11: Fuel properties summarization.

OBRÁZEK 11: Souhrnný popis vlastností paliva.

The assessment of the impact of fuel composition variations on vehicle performance can be performed using just tabulated fuel properties as an input into the consideration and/or calculation. This fact simplifies the assessment process itself. On the other hand, the maneuvering space for compensation of possibly unfavorable fuel properties is limited. In this way the demand for the future orientation of gas-fueled vehicle fleet development towards a mono-fuel optimized arrangement is emphasized.

The use of hydrogen-containing gases as a fuel for contemporary conventional gas fueled vehicle design is possible as long as the fuel's inherent drawbacks (mainly limited vehicle range) are accepted as inevitable. Therefore, the presence of the existing vehicle fleet does not present a major obstacle to the introduction of gaseous mixtures with a high content of hydrogen into the vehicle gaseous fuel market.

In Figure 11 the demand for dimensioning of the engine fueling system is also presented. The value Qfuelt describes the actually measured sum of the consumptions of both NG and hydrogen. The curve Qfuelt displays theoretical fuel demand in order to maintain original (i.e. that obtained with NG) engine power. The increased demand with respect to fuel line dimensions to cope with increased fuel flow is visible, but not crucial. It is the only necessary condition to enable the use of hydrogen-containing mixtures in existing vehicles. Any further rearrangements of conventional gas fueled engines are not required.

Despite the declared poor knock resistance of hydrogen, an excessive occurrence of knock is not expected during operation of naturally fueled engines, especially when the compression ratio is compatible with petrol fueled engines. The change of molar fraction of monitored pollutants in raw exhaust gas is visible, but still remains within a range which can be effectively elaborated by conventional exhaust after treatment.

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LIST OF SYMBOLS AND ABBREVIATIONS

AKR	Anti-knock device
BMEP	Brake mean effective pressure
BSHC	Brake specific heat consumption
bTDC	Before top dead centre
CV	Calorific value
EGR	Exhaust gas recirculation
GHG	Greenhouse gases
HR	Heat Release
IMEP	Indicated mean effective pressure
pCyl	In-cylinder pressure
PPP	Peak pressure position
RoHR	Rate-of-Heat-Release
TCyl	In-cylinder temperature
TDC	Top Dead Centre
TNG	Transit natural gas
VGT	Variable turbine geometry
WG	Waste gate – Boost pressure control by partially bypassing the turbine
WOT	Wide open throttle