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Heat loss comparison between hydrogen, methane, gasoline and methanol in a spark-ignition internal combustion engine

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Abstract

Understanding the heat transfer mechanism from the combustion gases to the walls inside an internal combustion engine is key in the search for higher efficiencies, higher power outputs and lower emissions. Current heat transfer modeling concepts have been reported to be inaccurate for hydrogen engines. To investigate the heat transfer mechanisms in a hydrogen engine, we have measured the instantaneous heat loss inside a spark-ignition engine at three locations. To determine the effect of the throttle position, compression ratio, ignition timing and air-to-fuel ratio in the entire parameter space systematically, techniques of Design of Experiments are applied. The experiment has been repeated for methane, gasoline and methanol to compare hydrogen with other fuels and to build a database for the development of a fuel independent heat transfer model. The paper shows that the effect of the engine factors is similar for all the fuels. However, the heat loss to the cylinder walls of hydrogen is only at the same level of that of the other fuels for very lean mixtures. The engine efficiency drastically reduces for rich mixtures as a consequence, indicating that a lean mixture in combination with boosting and external gas recirculation should be used to obtain high power outputs with high efficiencies for port fuel injected engines.

Keywords: internal combustion engine; heat loss; hydrogen; methanol; Design of Experiments

1. Introduction

It is well known that hydrogen is an interesting energy carrier or buffer because it can be produced in several renewable ways and used in a wide variety of applications. For transportation, research mainly focuses on fuel cells. Much less attention has been devoted to internal combustion engines (ICEs) on

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Nomenclature

ANOVA	analysis of variance
CCD	central composite design
CFR	Cooperative Fuel Research
CR	compression ratio
DoE	design of experiments
FCT	fully closed throttle
IGN	ignition timing
λ	air-to-fuel equivalence ratio
RSM	response surface method
RTD	resistance temperature detector
TP	throttle position
WOT	wide open throttle

hydrogen, since the ICE is often readily dismissed as a future prime mover, for its low efficiency (particularly at part load) and pollutant emissions. However, the ICE in itself is a scalable and sustainable technology, because it is made out of abundantly available and recyclable materials [1]. Furthermore, its efficiency is still being improved, with reported lab peak efficiencies up to 57% [2]. Consequently, it is still a possible future prime mover if sustainable fuels are used, hydrogen being an option. The unique properties of hydrogen indeed enable zero greenhouse gas and near-zero noxious emissions and a high efficiency throughout the load range [3]. Compared to a fuel cell, a hydrogen-fuelled ICE has the advantage of a reduced cost, both for the engine and fuel (lower purity needed). Furthermore, the same ICE can be run on several fuels, enabling a transition from the current fuels to hydrogen.

To enhance the ICE development, computer tools are being developed to simulate the engine cycle. An important part in these models is the prediction of the heat transfer inside the engine, since it has an effect on all three improvement targets: the power output, the efficiency and the emissions. The research on the heat loss in hydrogen engines indicates that the heat loss mechanism differs from other fuels [4, 5] and that existing models are not capable to capture that difference [6, 7]. To investigate the heat loss mechanism of hydrogen in comparison with that of other fuels, measurements have been carried out in a spark ignition engine on hydrogen, methane, gasoline and methanol. This paper investigates the effect of four engine factors on the heat flux in addition to that of the fuel: the throttle position (TP), the compression ratio (CR), the ignition timing (IGN) and the air-to-fuel ratio (λ). A systematic variation of the engine factors is needed [8], so techniques of Design of Experiments (DoE) have been applied.

2. Measurement method

2.1. Measurement equipment

The engine used in this research is a four-stroke single-cylinder spark ignition engine based on a CFR (Cooperative Fuel Research) engine operated at a constant speed of 600 rpm. A cross section is given in Fig. 1, showing the possible sensor positions in the cylinder wall. It is equipped with PFI (port fuel injection) and has a variable compression ratio. Two types of injectors are available in the intake manifold, one for gaseous fuels and one for liquid fuels. The injection and ignition is controlled by a MoTeC M4Pro electronic control unit. The compression ratio has to be kept below 10, because the moving piston would otherwise damage the heat flux sensor. The details of the engine are given in Table 1. It has recently been revised, resulting in a larger bore diameter and different valve timings compared to older publications.

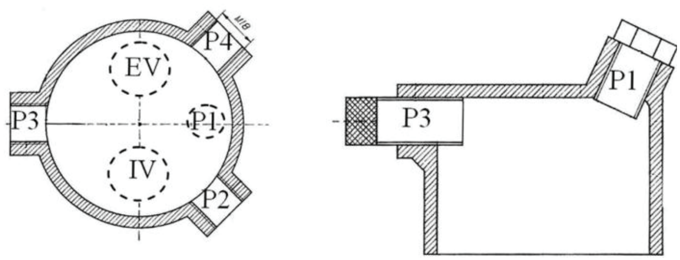

Fig. 1. Cross section of the CFR engine, P1: spark plug position, P2-P4: possible sensor positions, IV: intake valve, EV: exhaust valve

Table 1. CFR engine properties

Bore	83.06 mm
Stroke	114.2 mm
Connecting rod length	254 mm
Swept Volume	618.8 cm³
IVO	10 °CA ATDC
IVC	29 °CA ABDC
EVO	39 °CA BBDC
EVC	12°CA ATDC

The heat flux and wall temperature are measured at positions P2, P3 and P4 with a Vatell HFM-7 sensor which consists of a thermopile (heat flux signal, HFS) and an RTD (resistance temperature detector). Vatell claims that the sensor has a response time of 17µs. The Vatell AMP-6 amplifier was used as a current source for the RTD and as an amplifier for both output signals. The measurement positions are at the same height in the cylinder wall and are equally distributed around the circumference of the cylinder. The spark plug was mounted in position P1.

In-cylinder pressure was measured with a water-cooled Kistler 701A piezoelectric sensor (mounted in P4 or P2). Inlet and outlet pressure were measured with two Kistler 4075A10 piezoresistive pressure sensors. The inlet pressure was used to reference the in-cylinder pressure. Gas flows were measured with Bronkhorst Hi-Tec F-201AC (gas) and F-106BZ (air) flow sensors. Liquid fuel mass flow rate is measured gravimetrically. Finally, type K thermocouples were used to measure coolant, oil and inlet and exhaust gas temperatures.

All the signals were acquired with a National Instruments PXI system. Crank angle resolved signals (HFM and pressure signals) were acquired synchronously with a PXI-6143 S-series card every 0.5 °CA (sample rate of 7.2 kHz) during 100 consecutive cycles. The other signals were averaged over time and acquired with a PXI-6224 M-series card at a sampling rate of 1 Hz.

2.2. Experimental design

The experiment was designed according to DoE methods (Design of Experiments) described in ref. [9]. The purpose of the DoE is to vary the several factors in a systematic way and to define the minimum required number of combinations to investigate the heat flux in the entire parameter space, because it was not possible to run all the combinations.

The peak heat flux to the cylinder walls was the investigated dependent variable. A Response Surface Method (RSM), more specifically a Central Composite Design (CCD), will be used, so each factor will be tested at 5 levels (coded as -2, -1, 0, 1 and 2). Since the fuel and measurement position are categorical factors, they will not be included in the DoE design and the RSM will be repeated for the several levels of these factors (three times for the different measurement positions and four times for the different fuels). The levels of IGN and λ are fuel dependent to cover the optimal and widest possible range for each fuel. A combined wide range of IGN and λ is not possible for hydrogen, due to the occurrence of abnormal combustion at the extreme combinations (e.g. an early ignition for rich mixtures). Consequently, λ has been varied at the lean side for hydrogen to cover the widest possible range for IGN. Stoichiometric measurements will later be conducted to confirm the findings beyond the lean mixtures. An overview of the extreme levels of the continuous factors is given in Table 2.

Table 2. Overview of the factors' extreme levels

factor	fuel	level	level code
TP	all	fully closed throttle (FCT)	-2
		wide open throttle (WOT)	2
CR	all	8	-2
		10	2
IGN	methane	38°ca BTDC	-2
		10°ca BTDC	2
	hydrogen	5°ca BTDC	-2
		-15°ca BTDC	2
	gasoline	25°ca BTDC	-2
		5°ca BTDC	2
	methanol	25°ca BTDC	-2
		5°ca BTDC	2
λ	methane	1.2	-2
		0.8	2
	hydrogen	2.2	-2
		1.4	2
	gasoline	1.2	-2
		0.8	2
	methanol	1.3	-2
		0.7	2

A full factorial CCD, containing all the possible combinations, consists out of three parts. First, all the possible combinations of the factors at the levels -1 and 1, the so called cubical points, being used to test the main effects and interactions. Second, the extreme values of a certain factor (-2 or 2) at the center level of the other factors (0) to test non-linear effects of that certain factor. Third, the replication of the center point (all factors at level 0) to test the experimental error. Running the full factorial CCD for all the measurement positions for a certain fuel was not possible on one day, so a fractional factorial design with a reduction in the number of cubical points needed to be designed.

No information was available in literature on which interactions could be neglected, so the full factorial experiment was run in one measurement position (P2) on methane to provide this information. The Analysis of Variance (ANOVA) for the maximum heat flux of that experiment showed that all the main effects and the quadratic effects of IGN, TP and λ were significant. None of the interactions turned out to be significant. However, including the variation of the heat flux within the engine cycle (adding the degree crank angle as a factor), revealed that the first order interactions of IGN could be significant. Consequently, they were considered in the final design of the fractional factorial design. The degree crank angle was not kept as a factor in that final design, since the experimental model of the instantaneous heat flux does not accurately fit the measurements points in the entire parameter space, in contrast to that of the peak heat flux. To have a clean estimation of all the main effects and the interactions of IGN with CR, TP and λ, a fractional factorial design of half of all the possible cubical points could be run (8 instead of 16). The full factorial experiment on methane also showed that the effect of CR was linear, so the two most extreme values were not run for that factor in the fractional factorial design. Consequently, the final CCD design for each measurement position and fuel consists out of 16 combinations (2 center points, 6 extreme values and 8 cubical points), which means a total of 192 cases (=16x3x4).

3. Results and discussion

The statistical analysis of each CCD experiment results in an experimental surface of the maximum heat flux over the entire parameter space. The results are very similar for the three measurement positions, so only the results at one position (P3) will be presented here. None of the interactions between IGN and the other factors turned out to be significant, so the effect of a certain factor is independent of the level of the other factors. Consequently, the effect of a certain factor can be plotted at the center level of the other factors. In each graph plotted in the next sections, the mean value of the plotted line would change in case the level of the other factors would vary, but not the shape of the line.

In addition to the experimental surface of the maximum heat flux, surfaces can also be obtained for the indicated work. Fig. 2 plots the effect of the throttle position on the indicated work output for the different fuels. The left side of the graph (63°) corresponds with the WOT value and the ride side (87°) with the FCT value. The throttle has not been varied between 0° and 63° because this does not reduce the air flow and, hence, the work output (because of the low engine speed). Fig. 2 shows that the level of the work output differs between the fuels over the parameter space, having an influence on the peak heat flux value. Especially the work output on hydrogen (lean mixtures) can be significantly lower (up to 50%) than that of the other fuels. For hydrogen, the throttle position only affects the indicated work starting from 70°, because less air can flow into the engine due to the low density of the fuel. Therefore, to be able to compare the absolute values of the heat fluxes over the parameter space in addition to the factor effects, the heat flux has been corrected for the work output in the following graphs.

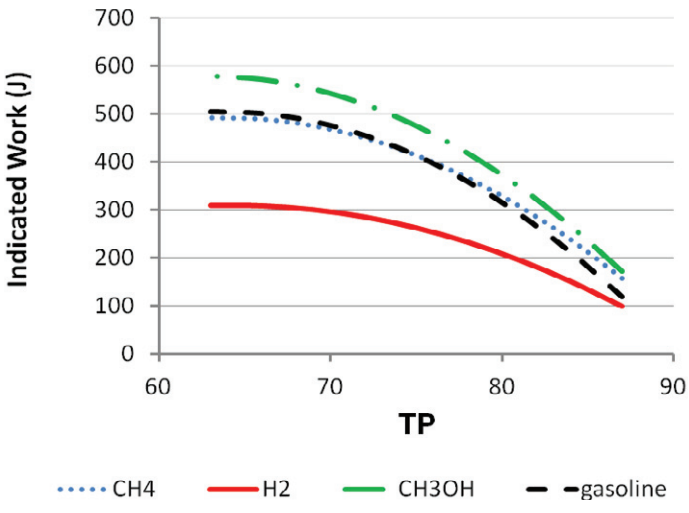

Fig. 2 The indicated work differs between the fuels over the parameter space

The effect of the throttle position and compression ratio on the peak heat flux is plotted in Fig. 3. The left side of the graph shows that the peak heat flux is reduced when the throttle opening is decreased, because the ingoing mass and, hence, released heat is reduced. The effect for the three fuels is very similar, with the average heat flux level going up from gasoline over methane and methanol to hydrogen. For the first three fuels, the heat flux slightly increases before dropping because the turbulence generated by the throttle counteracts the effect of the reducing ingoing mass, which has also been reported before [4]. For hydrogen, this effect is not visible in the heat flux trace. The throttle position must have a lower

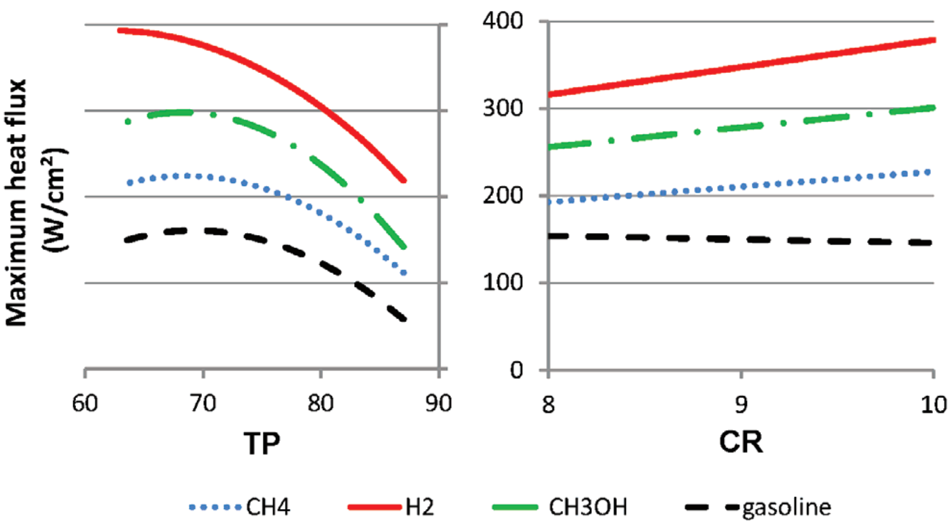

Fig. 3 The effect of the throttle position and the compression ratio

effect on the turbulence level of the ingoing flow, because of the long fuel injection duration. It is not plotted here, but the importance of the heat flux significantly increases when the intake flow is throttled. For methane for example, the total amount of heat losses to the walls, expressed as a percentage of the energy content in the fuel, increases from 30 to 45% going from WOT to FCT.

The right hand side of Fig. 3 plots the effect of the compression ratio. Increasing the compression ratio increases the heat flux because the cylinder pressure and, consequently, gas temperature rise. For gasoline, there does not seem to be an effect of the compression ratio, but this must be caused by a measurement error. Again, the average heat flux level increases from gasoline over methane and methanol to hydrogen.

The effects of the ignition timing and air-to-fuel equivalence ratio are plotted in Fig. 4. The left hand side of the graph shows that of the ignition timing, early ignition timings being at the far left side. The effect for all the fuels is again very similar (except for gasoline, which must be caused by a measurement error). The heat flux decreases linearly when the ignition timing is retarded, because the peak gas temperature is reduced. Hydrogen, again results in the highest heat flux levels.

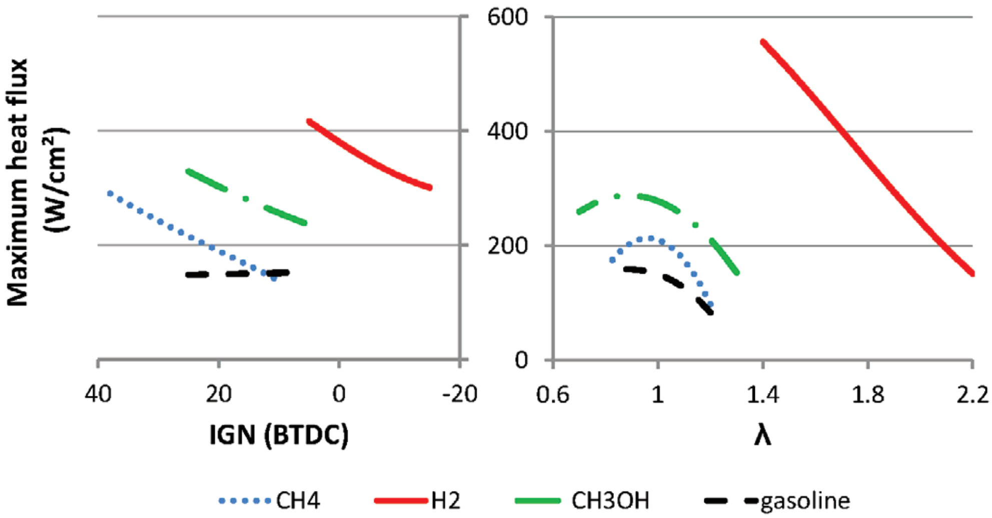

Fig. 4 The effect of the ignition timing and the air-to-fuel equivalence ratio

The effect of the mixture richness is plotted at the right side of Fig. 4. Gasoline, methane and methanol have been varied around the stoichiometric air-to-fuel ratio, resulting in a maximum in the peak heat flux at the rich side. The air-to-fuel equivalence ratio for which the heat flux peaks differs for each fuel. The maximum in the peak heat flux has not been reached for hydrogen, since only lean mixtures have been used as explained above. Extra measurements in the center level of the other factors will be run to find that maximum for hydrogen. It is expected that peak heat fluxes could be 3 times higher than that of the other fuels. However, for the first time in this paper, Fig. 4 shows that the heat flux level of hydrogen can be at the same level as that of the other fuels if lean mixtures are used. Earlier results already demonstrated the negative effect of the soaring heat flux on the engine efficiency for stoichiometric hydrogen mixtures in the CFR engine [10]. These results are repeated in Fig. 5 to demonstrate that the indicated efficiency drops from 29 to 23% because the amount of heat loss increases from 23 to 37% when the air-to-fuel ratio is changed from 2 to 1. The indicated efficiency does not drop as strongly as the increase in the heat loss because the combustion efficiency improves. Similar results have been shown on a production type engine [11], so lean hydrogen mixtures should be used to obtain very high engine efficiencies for port fuel injected engines. To reach high power outputs while maintaining those very high efficiencies, supercharging in combination with EGR can be used [12]. This does not apply for direct injection engines, where stratification could be used to have lean mixtures near the wall.

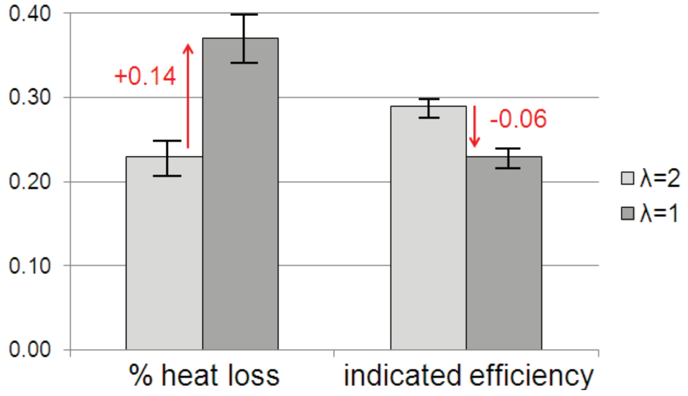

Fig. 5. The increasing heat loss for stoichiometric operation on hydrogen significantly reduces the indicated efficiency

4. Conclusions

This paper has presented instantaneous heat flux measurements in a spark-ignition engine. The heat loss of hydrogen was compared with that of gasoline, methanol and methane. The effect of the throttle position, compression ratio, ignition timing and air-to-fuel equivalence ratio have been investigated for all the fuels. Design of Experiments was used to determine the minimum required amount of factor combinations that needed to be run.

The paper showed that the effect of the engine factors were very similar for all the fuels. Only for very lean mixtures, the heat loss to the cylinder walls of hydrogen turned out to be at the same level as that of the other fuels. The results also indicated the negative effect of the higher heat losses for richer mixtures on the engine efficiency. Consequently, to maintain a high engine efficiency throughout the entire load range, boosted and lean hydrogen mixtures should be used in combination with EGR for port fuel injected engines.

The presented dataset can now be used, together with that obtained on motored operation [13], to investigate the possibility of a fuel independent heat transfer model. In contrast to the maximum heat flux discussed here, the instantaneous heat flux will be investigated for that purpose to include the variation within the engine cycle.

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