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Heat Transfer Comparison between Methane and Hydrogen in a Spark Ignited Engine.

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Abstract

Hydrogen is one of the alternative fuels which are being investigated at Ghent University. NO_x emissions will occur at high engine loads and they are a constraint for power and efficiency optimization. The formation of NO_x emissions is temperature dependent. Consequently, the heat transfer from the burning gases to the cylinder walls has to be accurately modelled if precise computer calculations of the emissions are wanted. Several engine heat transfer models exist but they have been cited to be inaccurate for hydrogen. We have measured the heat flux in a spark ignited engine with a commercially available heat flux sensor. This paper investigates the difference between the heat transfer of hydrogen and a fossil fuel, in this case methane. Measurements with the same indicated power output are compared and the effect of the heat loss on the indicated efficiency is investigated. The power output of hydrogen combustion is lowered by burning lean in contrast to using a throttle in the case of methane. Although the peak in the heat flux of hydrogen is 3 times higher compared to methane for a high engine power output, the indicated efficiency is only 3% lower. The heat loss for hydrogen at a low engine load is smaller than that of methane which results in a higher indicated efficiency. The richness of the hydrogen-air mixture has a great influence on the heat transfer process in contrast to the in-cylinder mass in the case of methane.

1 Introduction

Researchers worldwide try to find an alternative for fossil fuels to reduce the CO_2 emissions and to secure the energy supply. There is no silver bullet, so several possibilities are being investigated at Ghent University. One of them is the hydrogen-fuelled combustion engine. Research has proven that the combustion properties of hydrogen enable to achieve a high efficiency for all engine loads by using several operational strategies [1]. Moreover, hydrogen engines have near-zero noxious and zero greenhouse gas emissions. All this makes them an attractive alternative for the current drive trains.

The initial research at Ghent University was focused on the experimental optimization of engine operation strategies for maximum power and efficiency, with ultra low nitric oxide emissions [2-4]. The focus shifted to numerical research with the development of a thermodynamic model of the engine cycle, the GUEST-code (Ghent University Engine Simulation Tool) [5, 6]. Such a model of the engine cycle enables a cheap and fast optimization of engine settings for operation on hydrogen. Several sub models are necessary to solve the conservation equations of energy and mass: a combustion, a turbulence and a heat transfer model among other things. The last one is important to simulate accurately the emissions of oxides of nitrogen which are influenced by the maximum gas temperature.

These emissions will occur in hydrogen internal combustion engines at high loads and they are an important constraint for power and efficiency optimization.

Several heat transfer models for internal combustion engines exist in the literature. The models of Annand [7] and Woschni [8] are mostly used. They have however been developed for fossil-fuelled engines and they have been cited to be inaccurate for hydrogen engines [9-11]. The purpose of the current research is to investigate the cause of the difference in the heat transfer process and to indicate the missing components in the heat transfer models. We have measured the heat flux in a spark ignited engine with a commercially available heat flux sensor. The engine was run on hydrogen and methane to be able to compare the heat transfer process of hydrogen with that of a fossil fuel. The separate influence of the compression ratio, the ignition timing and the air-to-fuel equivalence ratio on the heat transfer of both fuels has previously been described [12, 13]. This paper compares measurements on hydrogen and methane with the same indicated power output. The power output for hydrogen was varied by altering the air-to-fuel equivalence ratio (λ). In contrast, a throttle was used in the intake manifold for methane to equalise the power output with the hydrogen measurements.

2 Experimental Equipment

The engine used for the measurements is a four-stroke single-cylinder spark ignited gas engine based on a CFR (Cooperative Fuel Research) engine operated at a constant speed of 600 rpm. It is equipped with port fuel injection (PFI) and has a variable compression ratio. The details of the engine are given in Table 1. A cross section of the CFR-cylinder is shown in Figure 1. Fuel injection and ignition timing are controlled by a MoTeC M4Pro electronic control unit.

We have used a commercially available sensor to measure the heat flux and wall temperature. It is a Vatel HFM-7 sensor which consists of a thermopile (heat flux signal, HFS) and an RTD (substrate temperature signal, RTS). The sensor has a response time of 17 μ s. As the test engine is easily accessible, the heat flux sensor was installed in three different positions (P2, P3 and P4 as shown in Figure 1). These openings are placed at the same height in the cylinder wall and are equally distributed around the circumference of the cylinder. The spark plug was placed in position P1.

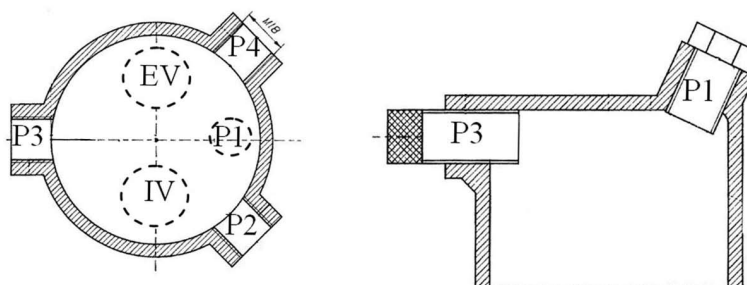


Figure 1: Cross section of the CFR engine, P1: spark plug position, P2-P4: sensor positions, IV: intake valve, EV: exhaust valve.

Table 1: CFR-Engine specifications.

Bore	82.55 mm
Stroke	114.2 mm
Connecting rod length	254 mm
Swept Volume	611.7 cm ³
IVO	17 °CA ATDC
IVC	26 °CA ABDC
EVO	32 °CA BBDC
EVC	6 °CA ATDC

In-cylinder pressures were measured with a water-cooled Kistler 701A piezoelectric pressure sensor and inlet pressure with a Kistler 4075A20 piezoresistive pressure sensor. This inlet pressure was used to reference the in-cylinder pressure around bottom dead centre (BDC) at the end of the intake stroke. A 12 bit data acquisition card was used to sample both the heat flux and pressure signals. It is triggered by a crank angle encoder every 0.5 °CA. This results in a sampling rate of 7.2 kHz. Gas flows were measured with Bronkhorst Hi-Tec F-201AC (fuel) and F-106BZ (air) flow sensors. Type K thermocouples were used to measure inlet and exhaust gas temperatures.

3 Results and Discussion

Three different air-to-fuel equivalence ratios for hydrogen were selected ($\lambda = 1, 1.5$ and 2). These three levels of mixture richness correspond with three different engine loads. The in-cylinder pressures are plotted in Figure 2 with a solid line in black, red and blue. An air-to-fuel equivalence ratio of 2 corresponded to an indicated work output (W_i) of 287J, which resulted in an indicated mean effective pressure (imep) of 4.7 bar. An air-to-fuel equivalence ratio of 1.5 gave 327J (imep=5.3 bar) and the stoichiometric combustion ($\lambda=1$) resulted in 376J (imep=6.1 bar). These three engine loads were repeated for methane and the results are plotted in Figure 2 as well, with a dotted line and in the corresponding colours of black, red and blue.

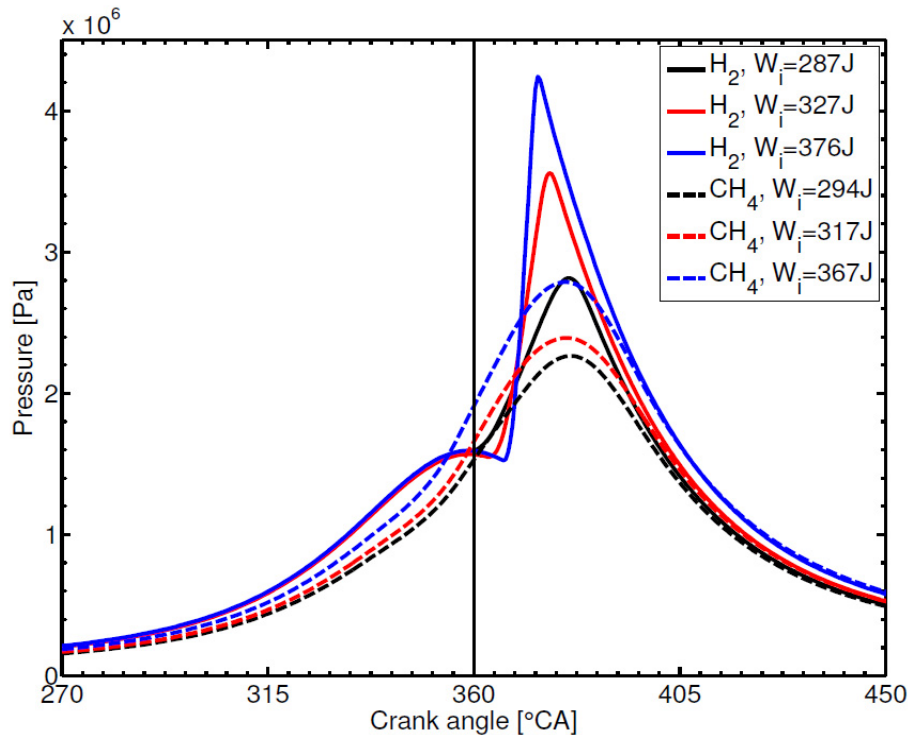


Figure 2: The pressure traces demonstrate the difference in combustion behaviour. Hydrogen burns faster than methane which causes the pressure trace to soar and to reach a higher maximum.

Methane combustion does not allow a variation of the air-to-fuel equivalence ratio in a wide range so a throttle in the intake manifold had to be used to decrease the power output, λ is kept equal to one. The throttle position can be varied between 0 and 90°. A change in the position between 0 and 70° does not have an effect on the power output because of the very small engine speed (600 rpm) and hence small air flow into the engine. A further small change in the throttle position has a large effect on the power output, so it is difficult to equalise accurately the power output with the hydrogen measurements. The throttle position of the methane measurement with a work output of 294J was 77°, that of 317J was 76° and that of 367J was 74°.

The pressure traces in Figure 2 show the difference in the combustion characteristics between hydrogen and methane. The hydrogen mixture burns very fast which causes the pressure to peak in a short time, the peak pressure goes up to 42 bar. Methane burns slower and this results in a wider pressure trace and a lower peak, up to 28 bar. The combustion properties have an influence on the chosen ignition timing. All the measurements were taken with ignition timing at MBT (minimum spark advance for Maximum Brake Torque). This MBT-timing is 23° ca before TDC for methane (not affected by a throttle variation) and it varies between 4° ca before TDC ($\lambda=2$) and 6° ca after TDC ($\lambda=1$) for hydrogen.

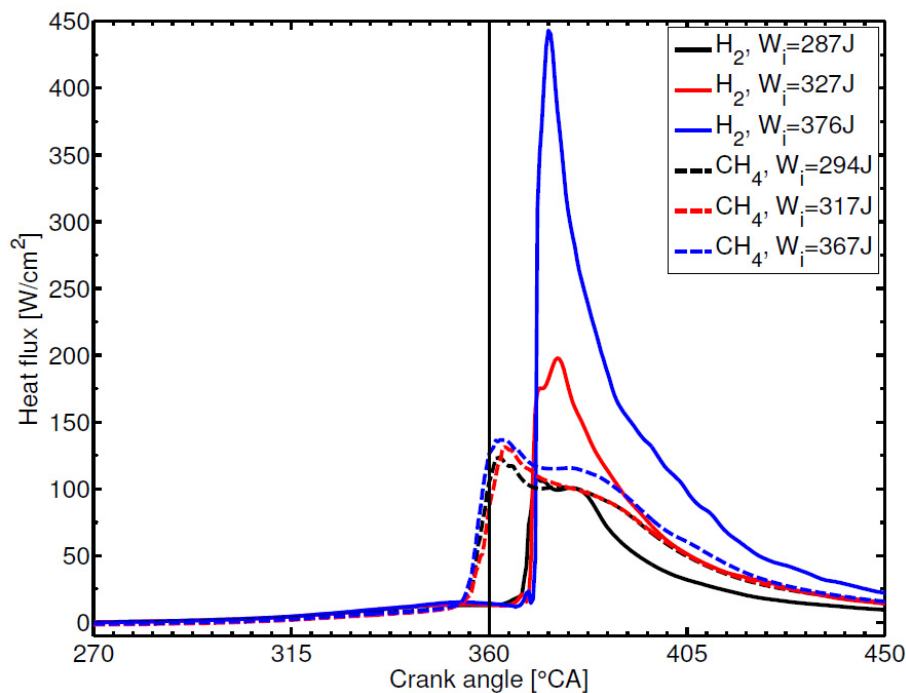


Figure 3: Varying the engine load by 23% results in a variation of 80% in the heat transfer of hydrogen and only 13% in that of methane due to the difference in load control.

The corresponding heat flux measurements in position P2 are plotted in Figure 3, those of hydrogen with a solid line and those of methane with a dotted line. The initial rise in the heat flux traces is caused by the flame passage over the measurement position. Although the flame speed is slower for the leanest hydrogen measurements (black colour), the initial rise occurs at the same moment of the stoichiometric measurement (blue colour) due to the advanced ignition timing. The fast and short combustion of the stoichiometric hydrogen mixture generates a high peak in the heat flux trace. This peak greatly reduces with decreasing mixture richness. The peak in the heat flux trace reduces with 80% if λ is changed from 1 to 2. The resulting power output decreases with 23%. In contrast, the heat flux traces of methane remain almost the same. Reducing the in-cylinder mass has a large effect on the resulting power output, but not on the heat transfer. The heat transfer does decrease when the load is reduced, but not as much as expected. The extra turbulence generated by the throttle could be the cause, because the same trend was visible in measurements under motored conditions [12]. The mixture richness on the other hand has a great influence on the heat transfer process. The peak in the stoichiometric heat flux trace of hydrogen is 3 times higher compared to methane, but it is smaller if λ is equal to two. The difference in the heat transfer process is reflected in the indicated efficiency of the engine. To demonstrate this, an estimate of the total cycle heat loss is calculated assuming that the heat flux at P2 represents the heat flux over the entire cylinder wall. Each sampling point of the heat flux trace is multiplied with the available in-cylinder surface at that instant and all these values are summed up to calculate the total cycle heat loss. These results are given in Table 2 together with the details of the measurements. For hydrogen the total cycle heat loss decreases from 597J to 235J if the power output is reduced from 367J to 294J, which is a

reduction by 61%. The heat loss through the cylinder walls for methane reduces from 386J to 343J which is only a reduction by 11%.

Table 2: Details of the measurements.

fuel	ignition (°ca BTDC)	λ	throttle	W_i (J)	imep (bar)	η_i (%)	heat loss (J)
hydrogen	4	2	WOT	287	4.7	29	235
methane	23	1	77°	294	4.8	25	343
hydrogen	-2	1.5	WOT	327	5.3	26	353
methane	23	1	76°	317	5.2	25	329
hydrogen	-6	1	WOT	376	6.1	23	597
methane	23	1	74°	367	6	26	386

The indicated efficiency is lower for hydrogen in the case of the highest power output, 23% compared to 26% for methane due to the higher heat loss. The high efficiency caused by the fast combustion process of hydrogen counters partially the high amount of heat loss through the cylinder walls. Although there is a difference of 10% in the total cycle heat loss between hydrogen and methane at this power output level, there is only a difference of 3% in the indicated efficiency. The indicated efficiencies for both fuels are almost the same for the middle power output. The indicated efficiency of hydrogen is higher than that of methane for the lowest engine load, 29% compared to 25%. All this demonstrates the advantages of hydrogen as a fuel. The combustion properties enable a high efficiency for low engine loads, because there is no need to use a throttle. The efficiency is lower for the highest engine load in this case, but supercharging in combination with external gas recirculation could be a solution to attain high engine loads without high heat losses [14].

4 Conclusion

This paper has presented heat flux measurements in a spark ignited engine. The engine was run on hydrogen and methane to compare the heat transfer of hydrogen and a fossil fuel. Measurements with the same power output have been put side by side. The results showed that the heat flux of hydrogen decreased substantially if the equivalence ratio (and therefore the engine load) was reduced. In contrast, the heat flux of methane did not decrease that strong if the in-cylinder mass was reduced to attain lower engine loads. The peak in the heat flux was much higher for hydrogen compared to methane for the highest power output, but it was lower for the lowest power output. The mixture richness clearly has a large influence on the heat transfer process in contrast to the in-cylinder mass which was controlled by a throttle in the intake manifold. Total cycle heat losses have been calculated out of the measured heat flux traces. This paper has shown that the trends in the heat flux losses were reflected in the indicated efficiency which was lower for hydrogen compared to methane for the highest power output, but it was higher for the lowest engine load. The extremely high heat losses generated by the combustion of a stoichiometric hydrogen-air mixture will have to be reduced to improve the engine's efficiency at high loads.

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