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# Experimental investigation of the effect of engine settings on the wall heat flux during HCCI combustion

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Homogeneous charge compression ignition (HCCI) engines are a promising alternative to traditional spark- and compression-ignition engines, due to their potential to achieve a high thermal efficiency and near-zero emissions of $NO_x$ and soot. In this work, the heat transfer from the bulk gas to the cylinder wall is measured during motored and HCCI operation in a single cylinder (CFR) engine fueled with *n*-heptane. Heat flux measurements in the cylinder wall and head show small spatial variation of the heat flux in the combustion chamber. Design of Experiments methods are applied to study the effect of the engine settings on the heat transfer. It is found that the inlet air temperature does not affect the heat flux under motored operation. Under fired operation, all engine settings affect the heat transfer, but none of their interactions are significant. The compression ratio and inlet air temperature have a quadratic effect on the peak heat flux and peak convection coefficient, whereas the mass fuel rate has a linear effect. For the total heat released, the compression ratio and inlet air temperature have a linear effect and the mass fuel rate has a quadratic effect on it. All engine settings affect the instantaneous heat flux.

## 1. Introduction

In recent years, alternatives to traditional spark- and compression-ignition combustion are being investigated due to increasingly stringent emission legislation combined with the pursuit of a low fuel consumption. One of the alternative combustion principles that has received much interest is homogeneous charge compression ignition (HCCI) [1,2], which allows achieving both a high thermal efficiency and near-zero emissions of $NO_x$ and soot [3]. This is obtained by the auto-ignition of a lean premixed fuel-air mixture through compression. Because the auto-ignition process is mainly driven by chemical kinetics, the combustion is very sensitive to the mixture temperature. Hence, the heat transfer from the bulk gas to the walls of the combustion chamber has a large effect on important combustion properties, such as the start of combustion and the burn duration. It also affects the formation of pollutants such as $NO_x$, which have a strong temperature dependent formation process. A lot of research has been conducted on the heat transfer in gasoline and diesel engines [4–7]. However, despite the importance of the heat transfer in HCCI engines, only a limited number of studies have been performed in which the heat transfer is measured experimentally.

Boggs [8] was the first to investigate the heat flux during HCCI operation. He used a coaxial type heat flux sensor with 5 surface thermocouples to measure the heat flux at the cylinder head of a CFR (Cooperative Fuel Research) engine. HCCI operation was obtained by heating the inlet air and using ethylene as fuel. The effect of the gas flow on the heat flux was investigated by comparing an unshrouded inlet valve with a shrouded inlet valve at multiple shroud positions. Only the case with a counter clockwise swirl motion produced a significantly lower heat flux. It was speculated that this was caused by the dissipation of kinetic energy by the spark plug hole. The effect of the combustion was investigated by increasing the mass fuel rate and the inlet air temperature compared to a base setting. Both variations resulted in a higher heat flux.

To be able to construct a heat transfer model for HCCI engines, Chang et al. [9,10] measured the heat flux in a gasoline fueled single cylinder engine with exhaust rebreathing. Thermocouples were mounted at 7 locations in the piston surface and 2 locations in the cylinder head. The spatial variation of the heat transfer was evaluated by comparing the instantaneous heat flux traces at the different locations and by performing a heat release analysis. They concluded that a local heat flux measurement accurately represents

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the global heat transfer, unless the fuel preparation caused fuel impingement or stratification. The validation of these results for other operating conditions, revealed that increasing the fuel rate and engine speed also increases the peak heat flux.

Hensel et al. [11,12] measured the heat flux in 2 gasoline fueled single-cylinder engines, also with exhaust rebreathing. The heat flux was measured in one engine with thermocouples mounted at 8 locations in the cylinder head and in the other engine at 3 locations in the cylinder head. They confirmed the conclusion of Chang et al. concerning the spatial variation when changing the injection timing, valve timing and mixture preparation. They also found that the heat flux increases when increasing the load and engine speed and when advancing the injection timing so the combustion occurs earlier.

Finally, Heinle [13] investigated the heat flux in a single cylinder engine fueled with *n*-heptane. HCCI operation was obtained by heating the inlet air. An exhaust valve was fixed to the cylinder head and equipped with 8 thermocouples to measure the heat flux. He reported an increase in heat flux when the engine speed and inlet temperature were increased and a decrease in heat flux when the inlet pressure and Exhaust Gas Recirculation (EGR) rate were increased.

In current literature, the investigation of the effect of the engine settings on the heat transfer has been limited to comparing the measured heat flux traces when varying one engine setting at a time. Opposed to this one-variable-at-a-time approach, in this work, measurements are conducted according to the Design of Experiments methodology (DoE) [14,15]. By applying this methodology, it is possible to investigate the effect of the engine settings in a systematic way and to take into account the possible interactions between them. The effect of the compression ratio, mass fuel rate and inlet air temperature on the peak heat flux, the shape of the heat flux trace and the total heat released is investigated.

To separate the effects of the gas flow and the combustion, two experiments are created: one under motored operation and one under fired operation of the engine. First, the spatial variation of the heat transfer is investigated by comparing heat flux measurements at the cylinder head with measurements at the cylinder wall. The accuracy of the measurements is validated by performing a heat release analysis and by checking whether deposit formation affected the measurements. To determine which engine settings and interactions have a significant effect on the peak heat flux, the ANOVA (analysis of variance) methodology is followed for both motored and fired operation. With the significant parameters found, an experimental surface is constructed showing the magnitude of the effect each engine setting has. The observed results are linked to the underlying physical phenomena by using the convection coefficient to separate the effect of the temperature difference between the gas and the wall from the effect of the gas properties. Finally, the effect of the engine settings on the shape of the heat flux trace is investigated.

## 2. Experimental equipment

**Table 1**
CFR-engine properties.

| | |
|---|---|
| Bore | 83.06 mm |
| Stroke | 114.2 mm |
| Connecting rod length | 254 mm |
| Swept volume | 618.8 $cm^3$ |
| IVO | 10° ca ATDC |
| IVC | 19° ca ABDC |
| EVO | 39° ca BBDC |
| EVC | 12° ca ATDC |

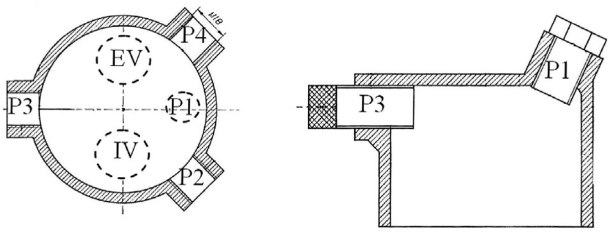

**Fig. 1.** Cross section of the CFR engine, P1-4: possible sensor positions, IV: intake valve, EV: exhaust valve.

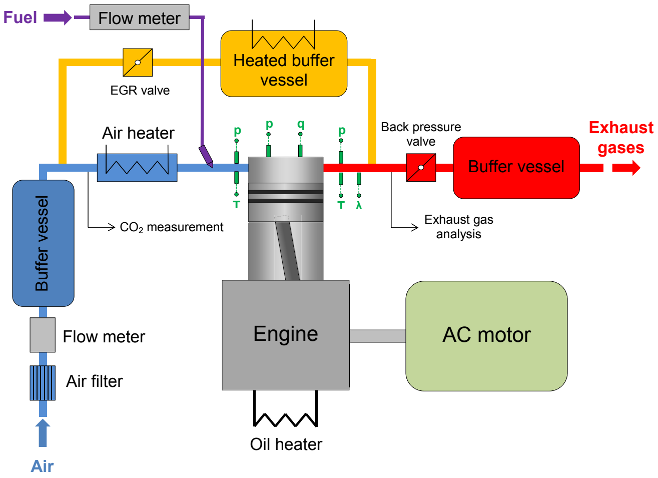

**Fig. 2.** Scheme of the engine.

The base engine used in this research is a Waukesha CFR engine. This is a standardized, overhead valve, single cylinder, four stroke engine. It is operated at a constant speed of 600 rpm and has an adjustable compression ratio. The engine specifications are listed in Table 1 and a cross section of the cylinder is displayed in Fig. 1, showing the possible sensor mounting positions. It is equipped with a programmable MoTeC M4 Pro Engine Control Unit to control the injection timing and duration. To obtain HCCI operation, an air preheating system and a heated external EGR circuit were added. However, no EGR was applied in this work. Fig. 2 shows a scheme of the engine layout. The intake air is heated with a 6 kW Osram Sylvania inline heater which is controlled by a Gefran 600 Temperature Controller to keep the temperature at the inlet within 0.5° C of the set value. The engine is fueled with *n*-heptane which is injected 180 mm before the intake valve to attain a homogeneous air-fuel mixture in the cylinder.

The in-cylinder pressure is measured with a water-cooled Kistler 701A piezoelectric sensor (mounted in P2). Inlet and outlet pressure are measured with two water-cooled Kistler 4075A10 piezoresistive pressure sensors. The in-cylinder pressure is referenced with the inlet pressure. The air flow is measured with a Bronkhorst F-106BZ flow sensor and the fuel mass flow rate is measured with a Bronkhorst mini Cori-Flow M13 coriolis mass flow meter. The heat flux and wall temperature are measured with a Vatell HFM-7 sensor mounted in position P1, unless indicated otherwise. The sensor consists of a thermopile (heat flux signal) and an RTD (resistance temperature detector). It has a claimed response time of 17 μs. A Vatell AMP-6 amplifier is used as a current source for the RTD and as an amplifier for both output signals. The sensor outputs are directly correlated to their measured quantities. The heat flux and wall temperature are obtained by applying the