

Investigations on the Heat Transfer in a Single Cylinder Research SI Engine with Gasoline Direct Injection

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ABSTRACT

In this work, heat loss was investigated in homogeneous and stratified DI-SI operation mode in a single cylinder research engine. Several thermocouples were adapted to the combustion chamber surfaces. The crank angle resolved temperature oscillations at the cylinder head and piston surface could thereby be measured in homogeneous and stratified operation mode. A grasshopper linkage was designed and adapted to the engine, to transfer the piston signals to the data acquisition device. The design of the experimental apparatus is described briefly.

For both operation modes the average steady-state temperatures of the combustion chamber surfaces were compared. The temperature distribution along the individual sensor positions at the cylinder head and piston surface are shown. Furthermore, the curves of the crank angle resolved temperature oscillations in stratified and homogeneous operation mode were compared. It is shown that the local temperature curves show large variations, depending on the operation mode.

Using these oscillations, the heat flux profiles were calculated and compared with each other. To calculate the heat flux at the surface of deposits and the deposit thickness, an approach was used, that allows consideration of multiple layers with different material properties and thicknesses.

The differences in the heat transfer characteristics are demonstrated for a variation of spark timing in stratified operation mode. For comparison the heat transfer characteristic in homogeneous operation mode is shown at reference spark timing. Finally, the determined heat losses were compared with the predictions of existing models for instantaneous wall heat transfer and rated.

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INTRODUCTION

Stratified operation with spray guided mixture preparation is a promising concept to reduce CO₂ emissions from SI engines with gasoline direct injection. The major reasons for the high efficiency at part load are the unthrottled operation and the high thermal efficiency because of the globally lean mixture. Another often named source for the high efficiency is the reduced wall heat transfer in spray guided stratified operation [1, 2], which is usually explained by an insulating air buffer between burnt mixture and the combustion chamber wall [3, 4].

Few investigations on crank angle resolved piston temperatures in DI-SI engines at fired operation have been published [5]. Just as little has been published about the wall heat transfer in DI-SI engines or even spray guided stratified operation mode.

Fieger [6] investigated the wall heat transfer on SI engines with fast-response surface-thermocouples in the cylinder head and found a good agreement with the wall heat transfer model of Woschni [7].

Weberbauer [8] and Hoppe [2] investigated the flame propagation and the wall heat transfer in homogeneous operation mode and spray guided stratified operation mode in a single cylinder research engine.

Weberbauer [8] showed that the flame propagation in spray guided stratified operation mode follows the spray cone of the injected fuel. Through his measurements he also found indications for a layer of incombustible gas around the flame near the wall.

Hoppe [2] measured the crank angle resolved cylinder head and piston temperature curves in homogeneous operation mode and in spray guided stratified operation mode. He compared the thereby calculated heat flux curves with the predictions of several established models and has found a good agreement of his measurements with

the model by Woschni. Hoppe presented the average heat flux curves in his work but didn't show the temperature distribution along the sensors or the individual heat flux at the sensors.

Koepple [5] investigated the instantaneous surface temperatures in a modern DI-SI engine. The spatial distribution of the crank angle resolved temperatures and the effects of spray cooling were shown for a segment of the piston but no investigations on the wall heat transfer in stratified operation mode were presented.

The subject of this work is the detailed investigation of the transient wall heat transfer in spray guided stratified operation mode. To encounter this task, 19 fast-response surface-thermocouples were installed on the surface of the cylinder head and the piston of a single cylinder research engine with gasoline direct injection. The spatial and crank angle resolved trends of the surface temperatures during a work cycle were investigated in stratified operation mode. For comparison an operating point in homogeneous mode was investigated on the same single cylinder research engine. With the temperature curves of the individual sensors at the cylinder head and piston, the wall heat transfer was calculated for the whole cylinder.

This paper is structured as follows. The next paragraph contains a description of the experimental setup, including the single cylinder research engine specifications and the measurement instrumentation. The adaptation of fast-response surface-thermocouples in cylinder head and piston is described. The positions of the temperature measuring points in the cylinder head and piston and the positions of additional combustion chamber temperatures in the cylinder-liner are shown. In the subsequent paragraph, the data transmission and data processing is described. After a brief description of the piston-data transmission the instantaneous heat flux calculation is shown. In the results section, the steady-state temperatures at the cylinder head, piston and liner are shown for a variation of spark timing in stratified operation mode and at reference spark timing in homogeneous operation mode. Afterwards the crank angle resolved temperatures at the individual sensors in the cylinder head and piston are shown at reference spark timing. The crank angle resolved heat flux calculated by the temperature curves is presented in the next paragraph. The measured results are described with the prediction of established wall heat transfer models. Hereafter the heat loss behavior at spark timing variation in stratified operation mode is demonstrated. Again, the measured data are compared with the model's predictions. Finally, the energies calculated by the pressure trace analysis, the temperature measurement and the exhaust gas emission measurement, are balanced and compared with the measured fuel consumption. The last section offers a summary of the presented investigations.

EXPERIMENTAL SETUP

Single Cylinder Research Engine

The single cylinder research engine used for these investigations is based on a Rotax 654 single cylinder production engine. The cylinder

and the cylinder head were replaced by in-house manufactured parts. The engine displacement was thereby reduced to 450 cc; the bore is equal to the stroke. The aluminum cylinder head has a pent-roof combustion chamber with four squish areas (see [figure 2](#)). A centrally mounted, piezo actuated fuel injector with an outward-opening nozzle and direct needle actuation was used. The injector and sparkplug were arranged in the middle of the cylinder head. The spark plug was mounted towards the flywheel side. The engine has two intake channels with guide elements. To generate a variable charge motion, the guide elements can block one half of each intake channel. The lower sides of the guide elements were blocked and the intake channels were rotated with an angle of 30° in opposite directions about the main flow axes [9]. The global charge motion was approximatively a forward tumble. The charge motion was adjusted in previous investigations to stabilize the fluid flow in spray guided stratified mode. This configuration of the guiding system remained constant for all operating points investigated in this study

A wet-running cylinder liner was used to reduce the bore of the production engine. The cylinder block and the cylinder head were cooled separately. The piston used was made of aluminum and has a flat geometry without valve pockets. Piston and liner together are standard parts of the Citroen engine "XU9S". The engine has a switchable piston spray nozzle. To avoid oil-spray influences on the investigations the nozzle was switched off in all shown operation points. To reduce the rotational non-uniformity of the engine, a flywheel was mounted. The engine specification can be found in [table 1](#). The cooling water was conditioned to 92 °C. A heat exchanger was used to condition the oil temperature by the cooling water.

Table 1. Engine specifications

Displaced Volume	450 cc
Stroke	83 mm
Bore	83 mm
Connecting Rod	144 mm
Compression Ratio	12:1
Number of Valves	4
Fuel	gasoline (euro-super RON 95)
Injection Pressure	200 bar
Injector Position	central
Injector Type	outward opening (piezo actuated)
Cooling System	cylinder head and block separated
Cooling Water Temperature	92 °C

Because of the spatial configuration of injector and spark plug the engine can be operated in spray guided stratified mode. A sectional view of the engine is shown in [figure 1](#).

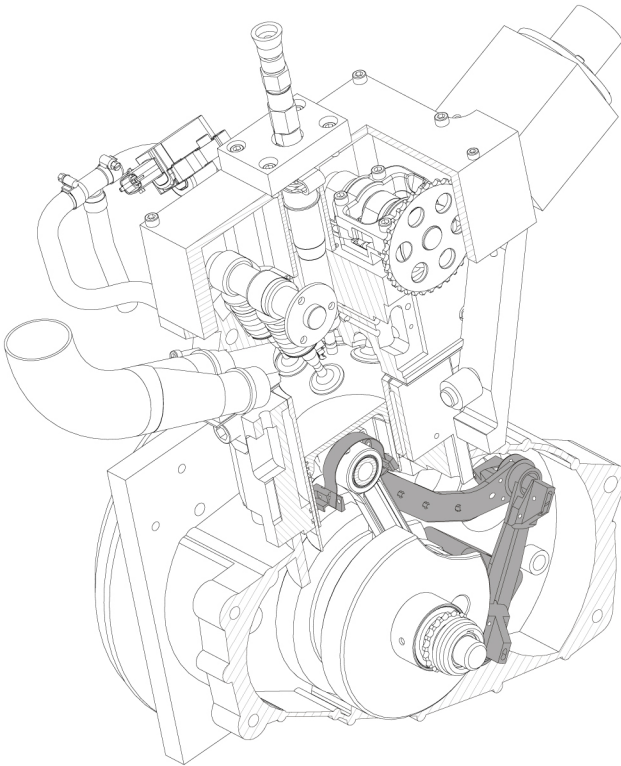


Figure 1. Sectional view of the single cylinder research engine with assembled grasshopper-linkage.

Measurement Instrumentation

High- and low-pressure indication was applied to the engine. To determine the heat applied to the process, the total heat provided by the fuel and the unburned fuel have to be balanced. Therefore the fuel consumption and the exhaust gas emissions were measured.

Fast-Response Surface-Thermocouples

In this work the instantaneous surface temperatures were measured crank angle resolved at several sensor positions on the piston and the cylinder head. By these temperature curves, the total heat flux of the combustion chamber was calculated. The detailed method is given in [10,11,12,13], [3] and shown below. A total of 19 fast-response surface-thermocouples was applied to the engine.

Four Sensors were applied to the Cylinder head (see positions 1 - 4 in figure 2). There was a sensor position between the intake and the exhaust valves.

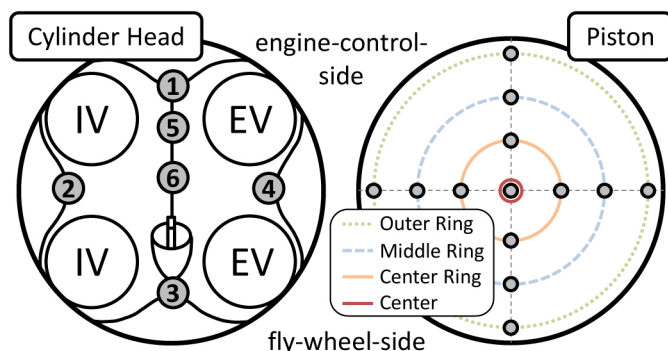


Figure 2. Top view of the surface-thermocouple positions through the cylinder head (left-hand side) and onto the piston top (right-hand side).

Additionally, there were two sensors applied in the ridge of the pent roof combustion chamber, each in a threaded sleeve to adapt the injector and the pressure transducer to the cylinder head (see figure 2 and figure 3).

An additional 13 sensors were applied in a cross pattern to the piston. They were arranged in the same cross sections of the engine as the sensors in the cylinder head (see figure 2).

Modified type k thermocouples with a diameter of 0.5 mm were used. The production process is described in [14]. During the production process the sensors are glued in with overlap, milled flush with the surface (in doing so the thermocouple junction is disjoined) and primed for vacuum coating. The components are then coated with chromium, whereby the thermocouple junction is formed again (but also an electric junction to the surrounding component). As a cover, the parts are finally coated with a thin layer of gold. The resultant thickness of the surface-thermocouples is in the order of 0.5 μm and the response time in order of 0.3 μs [14].

In contrast to the other sensors, the sensors in the adapter for the pressure transducer (Sensor 5, figure 2) and injector adapter (Sensor 6, figure 2) were manufactured at KIT and are sputtered, not thermally metallized.

The signals of the surface thermoelements were recorded synchronously with the pressure signals in the indication system with a resolution of 0.1 CAD.

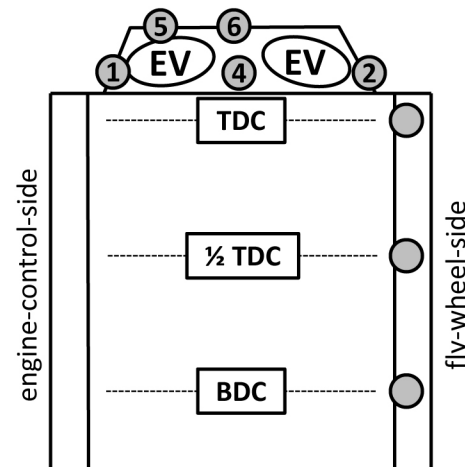


Figure 3. Surface-thermocouple positions in the cylinder head and thermocouple positions in the liner (crankshaft plane cross section).

Additional Combustion Chamber Temperatures

In addition to the fast-response surface-thermocouples in the cylinder head and the piston, three standard production thermocouples were applied to the cylinder liner. They were fitted 0.8 mm behind the combustion chamber wall at the fly-wheel-side at three different heights (see grey marks in figure 3). They were glued to radial blind bores. These three thermocouples are not as fast responding as the surface-thermocouples and the signals were thus not recorded on a crank angle resolved basis.

Data Transmission and Data Processing

The thermocouple wires were attached to a reference junction. On the piston, this junction was at the bottom side of the piston skirt. The reference junction for the other sensors was in a thermally insulated box installed beside the engine. At the reference junctions the wiring was changed from thermocouple cable to copper cable and the local temperature was measured with a thermistor.

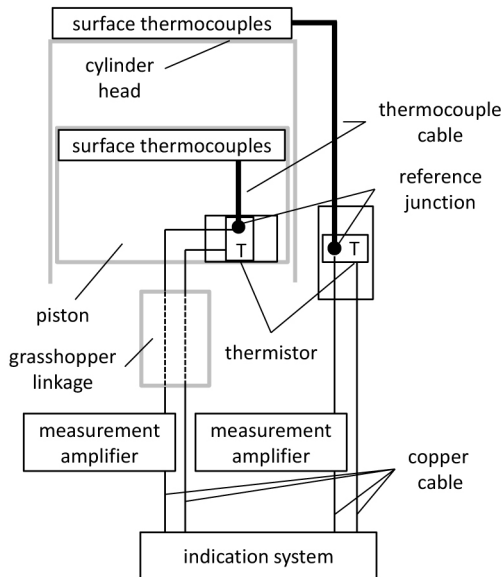


Figure 4. Measuring arrangement

The temperature measured by the thermistor was converted to a thermoelectric voltage referenced to 0 °C. The thermoelectric voltages from the surface thermocouple sensor were added to the voltage of the reference junction and the temperature of the Sensor was calculated using the NIST equations [15]. The measuring arrangement is shown in figure 4.

Piston-Data Transmission

Transferring the signals from the piston sensors to the recording system was a major challenge in these investigations. Wireless telemetry systems (see e.g. [2], [8] and [5]) and tethered systems (see [11], [16,17,18,19,20]) with several guiding solutions for the wiring are known for this purpose. For these investigations a grasshopper linkage was designed and adapted to the engine. The wiring from the reference junction on the piston to the grasshopper linkage runs along a flexible thin sheet of metal. Teflon coated copper cables with a diameter of 0.3 mm and flexible wires were used. The wiring along the linkage was bonded with RTV silicone. To reduce the torsional load the wiring was guided through the joint axes with a large distance. A detailed description of the design can be found in [21]. The piston with assembled grasshopper linkage can be seen in figure 5.



Figure 5. Piston with surface-thermocouples and assembled grasshopper-linkage.

Instantaneous Heat Flux Calculation

The transient heat flux can be calculated from the measured temperature oscillations. The detailed method is e.g. given in [10,11,12,13], [3] and [22].

The Fourier differential equation for transient temperature fields can be simplified to equation 1 assuming a one-dimensional temperature field:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} \quad (1)$$

Using Fourier series a closed-form solution for equation 1 exists, assuming steady state and a one-sided half-infinite wall:

$$T(x, t) = T_m - \frac{\dot{q}_m}{\lambda} x + \sum_{i=1}^{\infty} e^{-x \sqrt{\frac{i\omega}{2a}}} \left[A_i \cos \left(i\omega t - x \sqrt{\frac{i\omega}{2a}} \right) + B_i \sin \left(i\omega t - x \sqrt{\frac{i\omega}{2a}} \right) \right] \quad (2)$$

Considering the one dimensional heat transfer in equation 3,

$$\dot{q} = -\lambda \left(\frac{\partial T}{\partial x} \right) \quad (3)$$

equation 2 can be differentiated to equation 4. Thereby the heat flux on each position x in the combustion chamber wall can be calculated.