Abstract

In an environment characterized by advancing climate change and the rapid emergence of new solutions, development cycles for influential technologies such as the combustion engine must be shortened. Experimental measurement series form the basis for researching new approaches and developing precise simulation models. With the current state of measurement technology, physical measurands can be recorded with almost any resolution for static components. However, analyzing moving components such as the piston, which is also exposed to high temperature levels and acceleration forces, is only feasible with great effort. Although the piston in combustion engines plays a central role in the energy conversion process, recording the conditions prevailing there is expensive, complex and time-consuming, which is why many studies only consider piston measurements indirectly or with limited experimental and simulative approaches. This knowledge gap no longer fulfills the requirements in the conflict described at the beginning. In a literature study, documented solutions for measuring pistons were analyzed in order to derive the essential properties of these systems. This provided the framework for the development of a compact and lightweight telemetry system that mechanically decouples the piston measurement and thus allows a wide range of applications in different measurement scenarios for pistons and moving systems. In addition, the basis for measuring different physical variables was laid, while at the same time enabling flexible adjustment of resolution and energy consumption. A circuit design was developed from separately tested integrated circuits and, after analyzing the system properties in the laboratory, an installation process was developed to equip three pistons with the system. In combination with the installation of thermo couples, the software for energy-efficient measurement with customized resolution and optional transmission via Wi-Fi was developed with the first piston and its feasibility demonstrated. The second piston combined the telemetry system with a high-resolution surface thermocouple to develop a method for crank angle assignment in order to be able to measure and transmit surface temperatures with crank angle resolution. A third piston completed the findings through further series of measurements with varying operating conditions such as the use of alternative fuels. The result of this scientific work is a new telemetry measuring system that is able to record experimental data from moving components and should enable new solutions to be brought to market more quickly by reducing development times.

Chapter 1

Introduction

1.1 Motivation

The possibility to develop a society getting access to wares produced worldwide and enabling mobility for a vast majority of people relied to a large extent on the technology of combustion engines. However, due to progressing climate change, the concept of burning fossil fuel needs to be replaced by zero-emission technologies, which are not contributing to the worldwide carbon dioxide emissions. Right now, competitive technologies complying with zero-CO_2-emission are not existing, which is why in a first step low-emission approaches are inevitable. Electric drives and fuel cells are two approaches that have the potential to create a mobility with lower emissions and compete with combustion engines. Nevertheless, various use cases such as freight transport still rely on heavy-duty engines without the possibility to be replaced by zero-emission technologies at the moment. Concepts such as refuels and hydrogen allow to substitute fossil fuels to reduce CO_2-emissions while still relying on combustion engines. Using these alternative fuels for running combustion engines requires a re-engineering of the existing technology and, therefore, extensive investigations and development efforts. This includes all components of a modern engine, and while some components can be adopted easily, other parts with considerable emission reduction potential need to be evolved in significant development projects. As alternative fuels particularly affect the conditions existing inside the cylinder during the combustion process, primarily these components attract attention and need to be evaluated. Additionally, as climate change has progressed considerably, the time for developing CO_2-reducing products needs to be reduced. In particular, the possibility to analyze all components taking part in the combustion process motivates this thesis to support the development of future zero-emission technologies, preserve mobility for everyone, and ensure the transport of products all over the world without harming the worldwide climate.

1.2 Issue

Since the invention of combustion engines, many developments allowed to optimize emissions, efficiency and lifetime. While the concept is still the same, much effort was put into every single component, which is why today's combustion engines are a very advanced technology. Especially the combustion itself influences the emission output and efficiency of combustion engines. Therefore, many concepts and components for influencing the central process of burning fuel and transforming the chemical energy into a mechanical one were developed and optimized for the existing technology. Components such as air path or injector allow to monitor many important quantities and are part of multiple studies. On the one hand those components directly influence the combustion, on the other hand they are easy to access, which saves time when developing an improved engine generation while generating valuable information about what is happening inside the cylinder. Besides all other parts, especially the piston has an extensive influence on combustion, gas exchange and translation of chemical to mechanical energy. This is because of the translational movement of the piston that creates gas movement inside the cylinder and is used to actively interact with the injected fuel. Especially the speed of mixing and the quality of the air-fuel-mixture influences emissions and efficiency of the resulting process. However, the extraction of quantities regarding the piston is particularly challenging as it is a relatively small part oscillating with high velocities exposed to high temperatures. Therefore, quite often, the piston is not part of closer analysis to reduce development costs and time. Nevertheless, for creating new combustion concepts, which allow to use regenerative fuel or hydrogen with high efficiency and zero emissions, a deep understanding of how the piston influences those characteristics and what an ideal piston design looks like is needed. Existing systems for monitoring the piston are either difficult to implement in new setups or very costly. This complexity makes the analysis of piston characteristics expensive, time-consuming and inefficient. As a result studies often rather estimate or leave out piston quantities.

1.3 Aim of scientific research

As described before, the piston is a crucial component for optimizing emissions, efficiency and durability of combustion engines. The processes related to the piston as a reciprocating element, which strongly influences in-cylinder turbulence, gas exchange and combustion process, are complex. However, due to the importance of the piston, when trying to improve the engine technology, experimental data allowing to understand the influence of the piston is highly valuable. The scientific research done for this thesis aims to tackle the challenge of extracting essential quantities out of pistons in combustion engines. To fill the lack of data in existing studies, a development starting from a clean sheet of paper was done to create a device that is able to monitor piston characteristics with high accuracy and resolution in-situ while withstanding the extreme conditions like high temperatures and accelerations. Its features and dimensions ought to allow the application of the device in as many use cases as possible and costs to be low enough to maximize cost-benefit considerations. A system that is able to withstand the reciprocating accelerations inside a piston combined with high temperatures and an environment often including a lot of shielding steel components needs to have excessive durability. Other environments will often include less extreme conditions, which allows using such a system in various applications beyond its original use case. In the end, the application of the new device is supposed to create new knowledge about moving parts and pistons of combustion engines in particular, for accelerating the development of lower and finally zero emission technologies.

1.4 Structure

The first part of this thesis will give an overview about existing systems used in various studies on piston characteristics and described in the literature. This will allow to rate different approaches for monitoring piston quantities and create a basis to identify a promising approach when developing a new system. In the chapter afterward, the multiple steps for developing the new system will be presented and an extensive analysis of the characteristics and features of the new device will be described. A presentation of the test bench and the equipped pistons with installation and distribution of sensors follows. All experimental data generated with the new device in various situations and combinations is presented afterward. This starts with measurements done in an environment full of interferences like the test bench, which are used to verify the proposed abilities of the system, such as accuracy and measurement frequency. The second part will include an analysis of all data points generated with the equipped pistons, which allows to study the reliability of measurements during operation and an extensive thermal analysis of the piston itself. In the end the results of this thesis are summarized and some ideas on which future developments could improve the device are given in an outlook. A final statement will point out what new possibilities are created for developing efficient technologies, which lead to stop the contribution to the world wide CO_2-emissions.

Chapter 2

Fundamentals

2.1 Techniques for measuring piston characteristics

The central process inside a combustion engine is the transformation of chemical energy stored in the fuel into mechanical energy, resulting in the rotation of the crankshaft. An essential part of this process is the combustion, which takes place inside the cylinder and directly affects the head, liner and piston. While the head and liner are stationary, the piston actively influences the process of conversion. Meanwhile, the piston has to withstand high pressures arising during the combustion and transform them into a linear movement. This results in an oscillating motion with high acceleration and forces. Additionally, the flame often contacts the piston surface, which results in high thermal loads and, combined with the cooling from below, induces thermal stress. Besides that, the form of the piston is a vital feature to influence in-cylinder turbulence, the combustion process and air exchange. The piston influences wall heat losses, oil movement and formation of emissions, has to be light, and at the same time withstand all forces while sealing the combustion chamber. Furthermore, its safety is crucial to maintain engine operation as defects often lead to major damage. For developing efficient and clean engines, the understanding of such a central component is inevitable. The highly complex and transient processes make it difficult to create a deeper understanding when using modeling and simulation. Therefore gaining experimental data from pistons is a crucial puzzle piece for developing internal combustion engines. While there is a lot of interest in the characteristics of pistons, getting these measurements is rather difficult as accessing sensors inside the piston via wire is difficult due to the reciprocating movement. Nevertheless various approaches for analyzing piston performance via wired sensors were already tested and are presented in this section. Those approaches will be rated from very capable (++), capable (+), neutral (o), insufficient (-) and very insufficient (- -) regarding the categories complexity, precision, resolution, calibration, modifications, simplicity and durability for trying to answer the question what researcher could achieve with the chosen method.

Mechanical linkage

One of the first technologies developed for accessing experimental data of the piston was the mechanical linkage. In 1964 Furuhama et al. [1] realized a spring directly connected to the piston, which guided cables of ten thermocouples and could endure speeds up to 4000 rpm. Another setup included a connection directly through the combustion chamber, which allowed monitoring quantities of a two-stroke engine with speeds up to 8000 rpm. Later on, Furuhama et al. [2] enhanced their mechanical linkage system and integrated it into an automobile gasoline engine. With extending durability, measurements under real driving conditions were performed. This enabled extensive temperature measurements and even analysis of knocking, which represents extraordinary stress for the mechanical linkage. Further experiments were done by Westbrook et al. [3] for determining possibilities to extract data. Besides developing a miniature radio transmitter, the development of a direct-wired mechanical linkage system is described. Especially possibilities to measure temperature and strain are mentioned.

More interested in the piston's secondary motion and causes why piston slapping occurs, Munro et al. [4] used a mechanical linkage to study the diesel piston's transverse movement depending on its design. The pistons were equipped with miniature inductive displacement transducers to monitor the movement of the piston. Results could identify the importance of gudgeon pin offset, piston-liner clearance and gudgeon pin height. Trying to measure the instantaneous heat transfer through a piston, Mure et al. [5] utilized fast-response thermocouples. The measured surface temperatures transferred via a mechanical linkage were used to calculate the heat flux and develop a one-dimensional conduction model. Concentrating more on deposits growing in combustion chambers, Nakic et al. [6] used surface thermocouples transferred via a mechanical connection to monitor deposit growth in-situ. The relationship of the measured surface temperature was analyzed in dependence of resulting deposits on the piston. An extensive analysis of the heat lost to the walls in internal combustion engines was done by Choi et al. [7]. Therefore, cylinder head and piston were equipped with multiple instantaneous temperature sensors and various effects affecting the heat flux could be identified. To further investigate the combustion effects of gasoline engines, an optical engine facility was built up from Steeper et al. [8]. This included an optical liner and an optical piston connected through a mechanical linkage. With this, it was possible to observe local combustion phenomena. Preliminary investigations were conducted with surface thermocouples to create as realistic conditions as possible when using glass components. Sufficient lubrication of moving parts is crucial for a safe operation. Therefore, a reliable oil film has to be guaranteed for the piston as well as the connecting rod. Closer analysis of film thickness in a connecting-rod bearing was done with eddy current gap sensors and two thermocouples. The experimental results were compared with simulations for verification and made it possible to analyze bearing movement [9]. Taylor et al. [10] summarized fifteen years of literature, presenting projects, which include quantifying piston characteristics. This includes various measurement techniques and ways to extract data. The first part of the paper deals with the secondary motion of the piston measured by displacement sensors located in the piston skirt. Data extraction in those experiments was realized with a grasshopper linkage. Further usage of displacement sensors located in the top ring combined with thermistors made it possible to resolve piston ring motion like force, rotation and tilt. A piston equipped with fifteen thermocouples lying one millimeter below the surface was used to evaluate correlations between piston temperature and emissions. Piston temperature was therefore controlled by adjusting the cooling temperature and resulting thermocouple signals were transferred via a mechanical linkage making it possible to identify multiple correlations between emissions and piston temperature [11].

Conventional heat flux models have to be adjusted when applied to new combustion processes. Therefore Chang et al. [12] measured piston surface temperatures with various heat flux probes and transmitted signals via a mechanical linkage. A relative uniformity could be found and existing models were compared to measurements resulting in proposing a new model. Mufti and Priest [13] did extensive measurements of friction losses regarding engines. For isolating piston-related friction losses, strain gauges were located on the connecting rod for measuring axial forces and transmitted via a mechanical linkage. Deep insights into combustion and wall heat losses regarding a gasoline engine with direct-injection and different injection strategies, including stratified combustion mode, were given by Cho et al. [14] using fast response thermocouples. A detailed insight into the construction and wiring of the mechanical linkage with thermocouples is described. As thermocouple wires have very low endurance, a more durable steel wire is used to withstand the movement coming from the mechanical linkage. With changing the material before measuring the thermocouple voltage, the reference temperature has to be logged to calculate absolute temperatures, which was realized with a thermistor. The high mechanical load is one drawback of a mechanical linkage to a fast oscillating component like the piston. This results in a significant reduction of the lifetime as is discussed in this work. To estimate the thickness of deposits formed during combustion in an HCCI engine, Güralp et al. [15] equipped a piston with up to seven surface thermocouples. Accessing sensors via a mechanical linkage and monitoring heat flux during the fired operation made it possible to estimate deposit thickness from dampened temperature levels. Using a mechanical linkage for transmitting surface thermocouple voltages out of the piston, Emmrich [16] compared four different combustion modes, including heterogeneous and homogeneous combustion in two piston geometries. As assumed major differences regarding the heat flux were identified. Special interest was given to the delay of signal measurements through the conversion from analog to digital and backward. Measuring the delay in a separated setup revealed times of about 94 µs, which was used to correct the experimental data to achieve the best possible crank angle assignment. Focusing on the event of impingement, Cho et al. [17] combined the measurements of surface thermocouples with computational fluid dynamics (CFD) simulation. Experimental as well as simulative data demonstrated a drop in surface temperature in locations where fuel hits the piston and evaporates. Concentrating more on thermal stress of exposed locations inside the piston like the bowl, Kenningley and Morgenstern [18] equipped a piston with multiple fast response thermocouples for quantifying the thermal load in the bowl. Using those measurements, a FEM simulation was built up for a more detailed insight into effects leading to piston failure. The precision of existing empirical equations for calculating the heat loss within a combustion engine was reviewed in 2015 by Hügel et al. [20] for stratified mode in a gasoline engine. A grasshopper linkage monitored the surface thermocouples needed for monitoring the wall heat flux through the piston. This allowed the installation of thirteen sensors inside the piston in the form of a cross pattern.

The main advantage of directly accessing the sensors is the possibility to use data acquisition systems not restricted by space and power. This allows monitoring quantities with the highest resolution (++) and precision (++). Additionally, those systems do not need any calibration (++), which reduces errors during the measurement. However, it is pretty time-consuming to design a mechanical linkage connected to the piston as it has to be incorporated into the crankcase and should interfere with the piston motion as little as possible (Complexity --, Modifications -). As the crankshaft drive changes for different engines, the linkage has to be redesigned for every project (Simplicity --) and the reciprocating movement significantly reduces the lifetime (Durability -).

Thermal plugs

Another technology used for temperature analysis inside pistons are thermal plugs. With thermal plugs, the change in material strength depending on the exposed temperature is used for measuring piston temperature levels. However, due to its technology, only averaged maximum temperatures can be resolved (Resolution --). This includes high uncertainties regarding the precision (Precision --) and no possibility to cycle through multiple points or monitoring transient behavior (Durability o). A specific measurement plan is inevitable for creating reliable results. However, the design as a screw enables an easy installation inside the piston, which is why this method is used widely (Complexity +, Calibration ++, Modifications +, Simplicity --).

Lu et al. [21] equipped a marine diesel piston with multiple thermal plugs to study the temperature distribution of a new piston design. An additional numerical simulation of the piston temperatures is validated with the experimental data points. Using the verified model allowed the prediction of new piston designs with reduced heat losses. As already mentioned before, the precision of the measurement is a critical issue when using thermal plugs. To estimate the difference of actual temperatures versus the values logged with thermal plugs when conducting an ideal measurement, several experiments were executed by Madison et al. [22]. For those experiments two thermal plugs were located around one thermocouple. The data of the thermocouple is transferred via a wireless system presented later on. The measurement included operating in a stationary operating point for about four hours. While the thermal plugs change their material characteristics when exposed to elevated temperatures, the wireless system logs the temperature simultaneously. Deviations between both measurements of up to 10 % were recorded and especially the position was identified as an important factor regarding the precision. The development of new combustion strategies creates new challenges. In diesel natural-gas dual-fuel engines increasing temperatures, which exceed component limitations, are an issue. Fu et al. [23] studied new approaches for reducing piston temperatures. Therefore, a simulation model was created and validated with thermal plug measurements.

Optical

Various projects tried to use optical measurement technologies to access piston-related quantities. However, this often required setups of high complexity with multiple engine modifications. Additionally, often only averaged data could be generated and the combustion as well as reflecting components diminished the quality of the results. A rather exotic way of trying to measure the piston temperature inside a small utility engine was the approach of Ward [24] in 2004. A fiber Bragg grating was embedded into the piston surface and optical access was established through the liner (Complexity --, Modifications -, Simplicity --). Sending laser light through the fiber and measuring the shift in wavelength made it possible to record an averaged temperature along the way of light (Precision -, Resolution --, Calibration --, Durability o). Buono et al. [25] used an engine with an optical accessible head to test a technique where radiant energy from the piston is recorded (Complexity +). An optical probe was used to monitor infrared wavelengths radiated from the piston surface. The radiation intensity is converted to a voltage with a photodiode and allowed to calculate an integrated temperature. However, the signal generated during combustion had to be filtered and reflections from other surfaces interfered with the radiation of the piston (Resolution -). While the setup itself has the advantage of a low complexity and no piston modifications were needed (Modifications ++,