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On the development of novel telemetry systems for online monitoring of highly stressed components

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ABSTRACT

The energy and transportation sector are one of the biggest contributors to greenhouse gas emissions worldwide. While there are potentially cleaner and easily to apply options available for the operation of passenger cars, the usage of internal combustion engines in power generation and transportation systems such as ships and locomotives is still increasing. Consequently, there is a growing need for research focused on enhancing efficiency, reducing emissions, and minimizing lifecycle costs of these large engines. To achieve these goals, it is necessary to develop advanced measurement methods capable of quickly and precisely capturing difficult-to-measure parameters. Despite the simplifications provided by simulations, it is essential to validate these results through empirical measurements and to provide accurate input and boundary conditions for simulations.

This paper presents innovative telemetry systems developed for real-time monitoring of critical variables in highly stressed components such as valves, bearings, pistons, piston rings and others, even under harsh environmental conditions typical for internal combustion engines. These systems can measure multiple parameters such as temperatures, pressures or kinetic variables of mechanical components, providing invaluable data for engine optimization. The telemetry systems' design, including sensor placement, boundary conditions, mechanical considerations, and iterative design phases, will be thoroughly discussed.

Additionally, the paper will showcase results from experiments where multiple novel measurement technologies were employed, providing comprehensive insights into engine processes. These insights are crucial for the ongoing transition to alternative, carbon-free fuels and for further extending the service life of large engines.

1 INTRODUCTION

According to the UN Emissions Gap Report 2024 [1], the energy sector, which includes among others power generation and transport has a share of 68 % on the total global greenhouse gas emissions. According to [2], 5 – 7 % of the worlds carbon dioxide (or equivalent) emissions come from large engines, applied in the fields of construction and industry, power generation, marine and railway transport. In many of these applications, it is not feasible or recommended to replace the combustion engines with batteries or fuel cells. Therefore, a major pathway for developing carbon neutral systems is the use of alternative fuels, such as hydrogen, ammonia, methanol or others. This brings along new combustion concepts and injection methods [3]. Additionally, a further increase of the mechanical and thermodynamical efficiency is strived for. Commonly known levers for this are higher loads or compression ratios, minimization of mechanical losses, use of variable valve trains, etc. These measures result in a higher stress on the components of the power unit [4]. In order to further optimize these components fine-meshed monitoring directly on site is important. Therefore, the development of innovative, robust and compact sensor solutions is crucial. The results can be used in many different ways. Firstly, they can flow directly into the optimization of certain components or component geometries. Secondly, they can help to define the boundary conditions for simulations more precisely and thirdly, they can represent an independent validation of simulation results.

The present paper shall provide an overview about recent developments at the Large Engines Competence Center in the field of advanced sensorics and telemetry systems and provide a pathway for designing these measurement systems.

These developments include telemetry systems for measuring parameters on and around the piston such as temperatures, pressures and piston ring movement, but also other engine parts such as valve temperatures or liner distortion measurement, which is currently under development.

There are already numerous publications on this topic (e.g., [5], [6], [7]), but due to the large number of different situations and boundary conditions, every telemetry system is customized to a certain extent.

There are major differences, particularly with regard to the space available, the number of measurement channels, the power supply of the measurement electronics, the type of measured variables and the engine operating conditions in terms of achievable speed and load.

In the next chapter, these technical design parameters will be discussed in general. This is followed by detailed descriptions of selected telemetry systems and finally the graphical representation of measurement data and their validation.

2 DESIGN OF TELEMETRY SYSTEMS IN GENERAL

As briefly mentioned in the previous chapter, there are a few things that need to be considered regardless of the exact requirements of the telemetry system. These are generally defined here and corresponding solutions are described. This should serve as a kind of roadmap for the development of a telemetry system.

It is important to note that these steps usually cannot or do not have to be worked through exactly in the order displayed, but that, as in any development process, several iteration loops are required to achieve a satisfactory solution.

2.1 Clarification of scope

The first step is to clarify the requirements for the system. This involves defining the components to be measured and the physical variables to be measured. Are these variables, such as pressures or temperatures, which can be measured directly using state-of-the-art sensor technology, or does the sensor technology first have to be developed or tested in basic experiments? This point is directly related to the issue of the available budget, which should also be defined in this context.

2.2 Spatial conditions

Ideally, the space conditions can be checked using computer-aided design (CAD) data of the entire assembly with all potentially affected components. Using the example of a piston, this means that not only the piston itself must be considered with regard to the application of the sensor system, but also the entire crank mechanism including the liner and crankcase, as well as the kinematics, in order to rule out collisions.

If CAD data for the components concerned is not available, other means and workarounds are required to design the bulk size of the electronics and corresponding housing parts. These might involve rapid prototyping and the use of 3D printed dummy parts, which are softer than the parts in question and would not lead to a destruction of the assembly in case of a collision Figure 1.

Figure 1: 3D printed dummy for collision check

When selecting a material for FFF printing, it's essential to consider the specific requirements of your application, including mechanical strength, thermal resistance, biocompatibility, and budget constraints.

If space permits, the use of 3D scanners can be considered. However, it has been shown in the past that the use of these scanners can be very time-consuming, especially if the corresponding accuracy is required. In addition, the use of these scanners sometimes results in very large amounts of data that are difficult to process.

Another option that has proven practical in the past is the application of modelling clay.

This adheres to the components in question and deforms when the assembly is manipulated so that the spatial conditions can be modelled very well.

Table 1: Printable polymers for telemetry applications

Material	Advantage	Disadvantages	Use Temp
PLA	Biodegradable not warp inexpensive [8]	Poor mechanical properties rough texture brittle [8]	<50°C [9]
NYLON	Good mechanical properties Inexpensive wear resistance heat resistance [8]	Prone to warp High printing temperature [8]	<80°C [10]
PEI	Good heat resistance chemical stability good rigidity and strength [8]	High print temperatures, expensive, prone to warp, difficult to print [8]	<170°C [10]
PEEK	Good rigidity and strength Low density heat and chemical resistance [8]	High print temperatures Expensive prone to warp [8]	<250°C [11]

Figure 2: Modeling clay on a conrod for clarifying spatial situation – image kindly provided by SCHALLER Automation Industrielle Automationstechnik GmbH & Co. KG

An example of this technique is depicted in Figure 2, which was kindly provided by SCHALLER Automation Industrielle Automationstechnik GmbH & Co. KG.

Here too, however, there are clear limitations in terms of measuring accuracy, especially in comparison with the CAD method.

2.3 Mechanical design

The mechanical design of telemetry systems is crucial, not only regarding the lifetime of the measurement device and the parts to be measured, but also regarding the influence on the parameters to be measured. Therefore, a non-invasive (or as little invasive as possible) has to be strived for.

Hence, design principles such as form closure, positive mechanical engagement and lightweight design are of high importance. Technologies such as 3D printing are of great support for meeting these criteria. New materials, as described before, are capable of withstanding even the harsh conditions inside combustion engines. In addition, the use of techniques such as high-temperature adhesives and laser-welding is preferable to the use of screw or rivet connections.

2.4 Energy supply

In general, there are three ways of how to provide energy for powering the telemetry system.

The most straight-forward one is of course the use of a wire-based, external power supply [12]. The biggest advantage of this option is the virtually unlimited amount of energy which could be provided to the system. And if cables are already used for the power supply, which involves a certain amount of design work, the data can as well be transmitted by cable. This enables a large number of channels and high temporal resolutions. The biggest disadvantage of these solutions is the limitation in terms of achievable motor speeds and even then, the lack of robustness and longevity.

As an alternative to the wire-based solution, the energy could also be provided by batteries. This results in far less design effort and an increase in robustness. However, there are major disadvantages due to the limited capacity of the batteries and the maximum operating temperature. In certain situations, the weight of the battery can also play a role or lead to considerable relative increases in component mass.

Figure 3 shows an example of battery-powered piston temperature telemetry for high-speed applications (> 8000 rpm).

Figure 3: Battery-powered piston temperature telemetry

Based on the photo, it can already be concluded that the battery significantly increases the total mass of the piston, which can have an influence on the measured variables on the one hand and on the robustness of the system on the other.

The third option for powering a telemetry system is inductive charging. In this case, a receiving coil (RX) and respective capacitors are mounted on the moving part, whereas a transmission coil (TX) is mounted on the static system, in a position which is periodically passed by the receiving coil. When an alternating current (AC) is applied to the TX, a changing magnetic field is generated. Whenever the TX and RX coils overlap, a respective alternating current is induced into the RX coil. This current can be converted to a direct current (DC) and stored in capacitors and used up until the cycle starts again after one revolution of the crank shaft. For more detailed information about inductive power transfer, [13] is recommended. Compared to the battery, this method has almost exclusive advantages.

The system can be more compact and lighter and is repeatedly supplied with energy, ideally providing a never-ending measurement cycle as long as the robustness of the hardware is guaranteed. The only disadvantages are the need for more technical know-how and the fact that not only the moving but also the static components have to be machined in order to place both coils accordingly.

Figure 4 shows an example of an inductively powered piston temperature telemetry for high-speed applications.

Compared to the battery-powered system shown before, it is obvious that this system is lighter and therefore putting less stress on the components to be tested.

The last option to be discussed at this point is the possibility of energy harvesting. This term refers to the generation, provision and consumption of energy on the component under investigation itself. This can be implemented, for example, by using piezoelectric materials which, when deformed, release corresponding energy that is used to supply the telemetry. This technology is shown as an example in Figure 5. This is a system in which cylindrical piezo elements are arranged vertically.

This system is designed to be placed under railroad tracks. As soon as a train passes over the corresponding section of track, the piezo crystals are compressed and an amount of energy is released that is sufficient to supply a set of pressure sensors.

Figure 4: Inductively powered piston temperature telemetry

This allows conclusions to be drawn about the number and type of passing trains and their wheel condition following post-processing of the data. The aim here would be to predict rail wear.

One of the main advantages of this system would be its compact design and the fact that there is no need to process the surrounding static components.

Figure 5: Energy harvesting via piezoelectric elements

Figure 6: Energy harvesting via induction

However, the amount of energy that can be generated in this way is generally relatively low, which means that this technology cannot generally be used for all types of sensors or high-resolution systems.

It should be noted at this point that the exact implementation of energy harvesting can vary greatly and therefore the statements made here do not apply to all variants to the same extent. Figure 6, for example, shows a system consisting of an arrangement of permanent magnets and rotating coils that generate electrical voltage in accordance with the law of induction.

This system was designed to be mounted on a wheelset of a train, providing power for various types of sensors.

2.5 Measurement data

Finally, in most cases the telemetry systems have to be integrated into existing measurement and data recording systems. It is important to clarify which data acquisition rates are required, how these can be synchronized with existing data and whether post-processing of the data is necessary.

3 SELECTED TELEMETRY SYSTEMS IN DETAIL

Now that the criteria for the design and layout of telemetry systems have been described, this procedure will be illustrated using two practical examples. Firstly, the development and application of a system for measuring the temperature of the exhaust valves of a large engine is shown. The second example describes a system for measuring the kinetics of the piston rings of a large engine, both in the axial and radial direction.

3.1 Valve temperature

While the intake valves are not subjected to a great deal of stress due to cooling by the convection of the incoming air, the exhaust valves are among the most heavily stressed components of a combustion engine. They have to seal the combustion chamber against pressures of up to 250 bar (or more, in case of knocking events) and have to withstand gas temperatures of up to 2400 K. This is the adiabatic combustion temperature of a hydrogen engine at lambda 1. At lambda 2 it would be 1700 K or 1300 K at lambda 3 [14]. Depending on the fuel, the shape and design of the valve (e.g., hollow vs. solid), the combustion concept, the exact position on the valve etc., literature mentions exhaust valve temperatures between 400°C and 800°C at the bottom center [15], [16], [17].

Therefore, close monitoring of these crucial engine components is necessary. Valve temperatures have been observed long before ([18], 1943) and are easily accessible with wires, but in these cases the valve must be fixed in terms of rotation around its own axis so that the wires do not break.

However, a degree of freedom with regard to valve rotation is crucial to ensure even wear of the valve and thus efficient sealing over the entire service life [19]. And this is precisely the advantage of using telemetry systems for this measuring task.

In the following, the design steps mentioned in chapter 2 are applied step by step using the example of valve temperature telemetry.

3.1.1 Clarification of scope

The telemetry system should measure the temperature of one of the two exhaust gas valves at five different positions.

The symmetrically arranged temperature measurement positions are depicted in Figure 8 and Figure 9. Temperatures are monitored at the plate center and the plate edges, as they are considered the hottest spots of the valve using Type K thermocouples with a measurement range of -270 °C to 1260 °C and an accuracy of ± 2.5 °C. Additionally, the temperature close to the contact zone of the valve seats shall be monitored. All temperatures (except for the plate center) are positioned at a 0° and a 180° angle, in order to confirm simulation results regarding the symmetry of the heat distribution and monitor the rotation of the valve, if there is any.

3.1.2 Energy supply

It was already clear at the beginning of the considerations that there was not enough space available on a valve to provide the energy for 5 measuring channels with the corresponding time resolution via batteries. An energy supply via energy harvesting would have entailed considerable development effort and, moreover, it would not have been a promising approach from today's perspective in terms of the required high temporal resolution of the measurements. Solutions already available that provide the energy via cables were not pursued here, as these are based on the restriction of valve rotation and therefore would directly bias the parameters to be measured. For this reason, an inductive energy supply was used from the outset.

As mentioned in chapter 2.4 the setup consists of a transmission coil (TX coil), placed on the stationary reference system, sending energy to a receiving coil (RX coil), which is placed on the moving parts.

3.1.3 Spatial conditions and mechanical design

In this case, comprehensive CAD data was available, so the clarification of the spatial conditions was not an issue. As described in [20], for the first prototype, space was very limited, as the flexible printed circuit board (PCB) was mounted directly onto the valve. Another challenge of the prototype was that the transmitter coil for the inductive power transmission was placed outside the valve springs.

Due to the shielding caused by the springs, a very high voltage was required to provide sufficient energy for the telemetry. This induced a substantial heating of the components to be actually measured and was in the order of 100 W. “*Furthermore, this field generated electromagnetic inference in the measurement of the thermocouples, as their output voltage is on the millivolt scale.”* - [20]. A more detailed description of the prototype can be found in [20]. Due to the shortcomings of the prototype described above, the design was revised accordingly. The revision envisaged positioning the PCB on the retainer plate of the valve, as shown in Figure 7. This would have advantages above all in terms of space, as there would be significantly more room vertically, but also in terms of surface area on the board itself, which must have enough space for an analog digital converter (ADC), a microcontroller and a Bluetooth antenna. As the constraint on vertical space above the retainer plate is minimal for large, heavy-duty engines with overhead valve (OHV) configurations, two PCBs can be stacked on top of each other to improve the electrical performance of the telemetry.

In addition, the coils are not shielded from each other by the valve springs in this case. The updated valve telemetry design enhanced the inductive coupling between the transmitter and receiver coils. With the increased energy capacity, the telemetry can continuously sample the thermocouples and transmit data to the testbench.

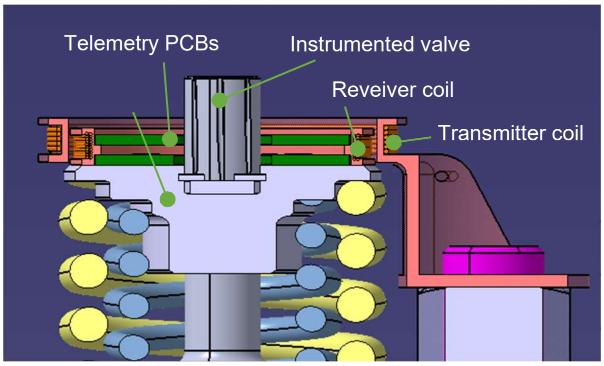

Figure 7: Cross section of the valve temperature telemetry setup

When the valve is open and the coils are separated, the telemetry is powered by a small capacitor bank on the upper PCB. This power is sufficient to sample six temperature channels at a rate of 50 Hz.

In order to implement this solution, it was important in the first step to exclude relative movement between the retainer plate and the valve itself so that the cables of the thermocouples would not run the risk of tearing.

This was achieved by placing marks on the retainer plate and the valve and operating the engine for a couple of hours. As there was no shift between the marks, it was confirmed that there is no relative motion between the valve and the retainer plate.

The second step was the mechanical design and the instrumentation of the valves. Machining the valves was a major challenge, as extremely long, precise holes were required to guide the thermocouples. These holes can no longer be produced using standard drill holes, but have to be produced using spark erosion. To make matters worse, the entry angle is <5° to the valve's axis. This operation requires a great deal of know-how and a number of technical tricks and was carried out by Instria s.r.o.

Not only the machining, but also the installation of the thermocouples requires a special manual skillset, know-how and experience.

The housings for the coils were designed in house and manufactured via 3D printing using high-temperature, high-stress materials.

3.1.4 Measurement data

The presented system uses precision delta-sigma ADCs to acquire thermocouple temperature data. First, the ADC's reference junction temperature is measured using an internal temperature sensor. The thermocouples' soldered connections to the PCB are positioned within 10 mm of the ADC to minimize offset errors caused by temperature gradients on the PCB. The voltage generated by the thermocouple's Seebeck effect is then measured by the ADC, following amplification by an integrated programmable gain amplifier (PGA). The telemetry's ARM Cortex-M33 microcontroller calculates the thermocouple's absolute temperature and transmits the data to the testbench in real-time via Bluetooth.

By reducing the number of integrated circuits (ICs) on the acquisition PCB, system scalability is enhanced.

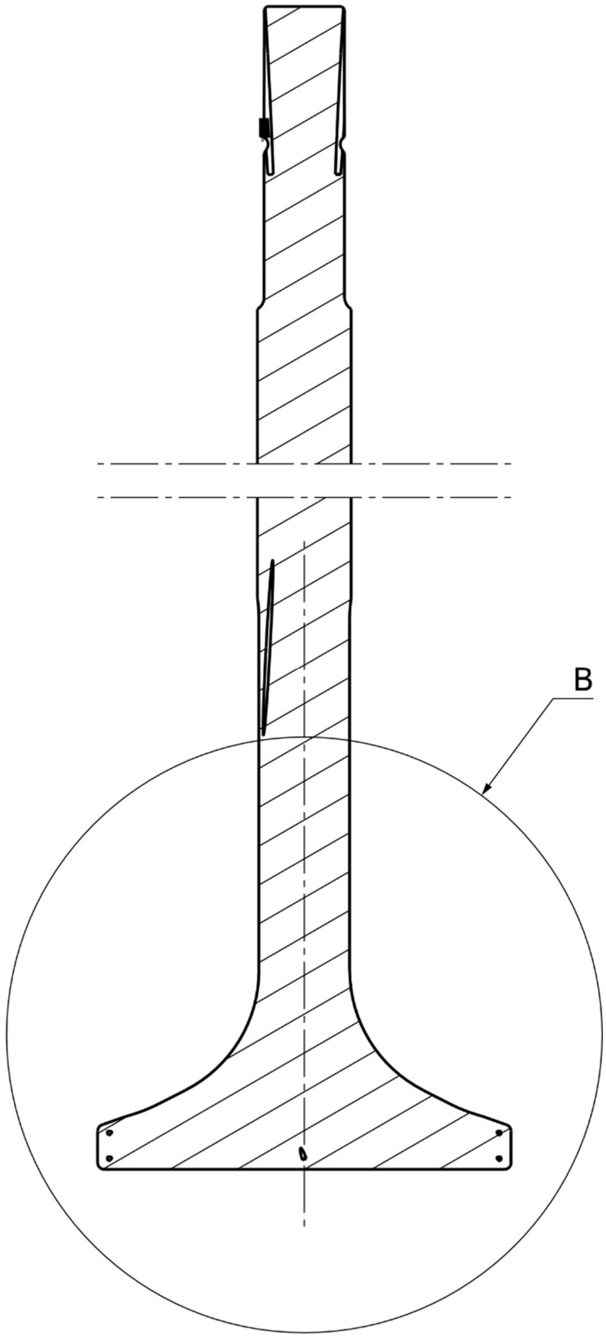

Figure 8: Exhaust gas valve cut-out with temperature measurement positions

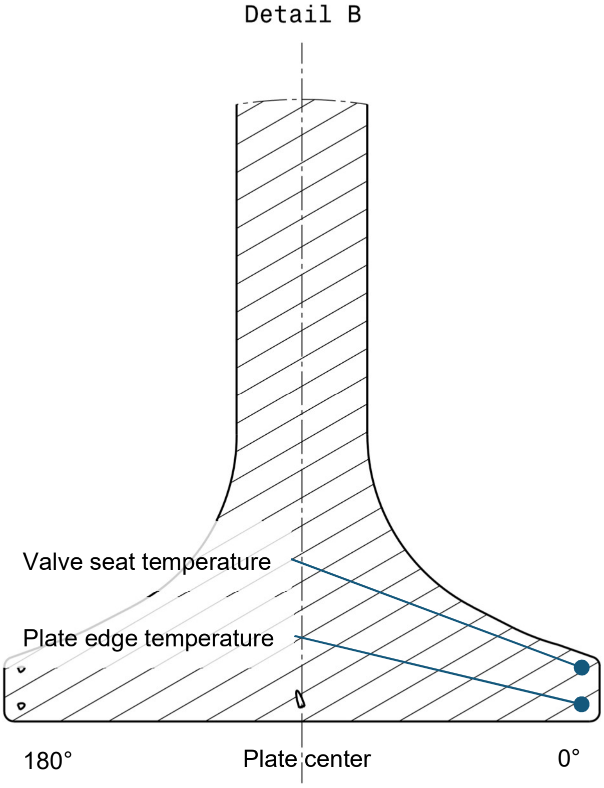

Figure 9: Exhaust gas valve cut-out with temperature measurement positions, Detail B

Finally, the measurement data was integrated into the data records of the KS Tornado test bench automation system. The corresponding data is described in the Results chapter.

3.2 Piston ring movement

This chapter will be dedicated to the kinetics of the piston rings. As the description and results of the axial ring movement have already been published in [7] and [20], this chapter will emphasize mostly on the ring rotation. However, for the sake of completeness, the axial piston ring movement telemetry will be summarized here as well.

3.2.1 Clarification of scope

A piston for a large heavy-duty hydrogen engine shall be equipped with a measurement system, capable of measuring temperatures all around the piston, the piston ring rotation and the axial ring movement.

In total, 49 thermocouples should be instrumented. For measuring the ring rotation, 24 of the 49 thermocouples are placed in the ring grooves. This is where one advantage of the telemetry system presented here becomes clear. Analog-to-digital conversion directly on the component is what makes it possible to provide such a large number of channels in the first place. In comparison, analog systems are often limited to approx. 8 sensors, as described in [21]. Compared to the use of so-called templugs, telemetry systems offer a number of advantages in general, including test management and the ability to perform online measurements. Also for the piston, the machining and a big part of the instrumentation was carried out by Instria s.r.o.

For monitoring the axial piston ring movement, eddy current sensors are being installed in the ring grooves. As the available power is limited and for detecting a ring lift a high temporal resolution is crucial, only one sensor per ring groove is installed.

3.2.2 Energy supply

In contrast to the valve temperature telemetry, there would always be enough space on the piston and conrod for a battery-powered supply of the sensors and chips. A battery of this size, which could be accommodated on the connecting rod in terms of space, is sufficient to supply 50 thermocouples with energy for around 100 hours.

However, replacing the batteries always involves a certain amount of effort. In addition, the operation of the eddy current sensors with the corresponding time resolution exceeds the capacity of the batteries of this bulk size. Therefore, the energy is also provided via inductive power transmission in this case. The transmission coil was placed in the crankcase, whereas the receiving coil was mounted directly on the piston, as shown in Figure 10.

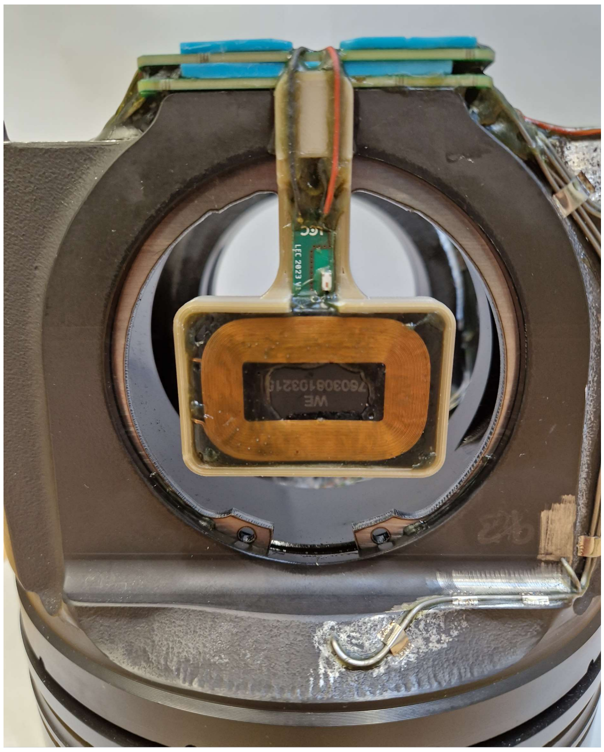

Figure 10: Piston telemetry assembly

3.2.3 Spatial conditions and mechanical design

As in the case of the valve telemetry, also in this case CAD data of all potentially affected parts was available.

Especially for positioning the TX coil it is crucial to check for collisions very carefully over the entire range of motion of the entire crankshaft drive over 360° crankshaft rotation.

At the same time, the distance between the TX and RX coil has to reduce to a max. of 5 mm, in order to transmit sufficient power to the telemetry every complete crankshaft rotation.

The PCBs containing the ADC converters could be stacked at the bottom of the piston without machining the piston or other parts.

The only design changes that had to be made were the holes for the thermocouples. As with the valve, these were produced using EDM machining.

3.2.4 Measurement data

For the temperature measurement, the data was sampled with 1 Hz and therefore integrated in the slow measurement data of the test bench automation system. As for other slow data, every measurement data point is the average over a 30 seconds' time.

Concerning the axial ring movement, the sampling rate had to be increased to 10 kHz in order to provide a crank-angle resolved monitoring of the ring movement. As data cannot be measured, processed and transmitted via Bluetooth in such a high frequency, the data is first stored on a buffer and transferred to the test bench system after the measurement is done, which is usually a period between 5-10 seconds.

4 RESULTS

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4.1 Valve telemetry

The valve telemetry was tested on a large heavy-duty engine operated with hydrogen at a constant speed of 1500 rpm. There was no measurement program specifically designed for testing the valve telemetry, however the telemetry system was recording valve temperatures over the course of several days of engine operation, during which no wear or change in performance of the whole system was noticed.

Following the experimental part of the measurement campaign, the results obtained were compared with data from simulations and verified, as will be shown in the next chapters.

4.1.1 Experimental data

As mentioned before, valve temperatures have been recorded over the course of several days.

The most important findings of this measurement campaign are explained by way of example in the next two diagrams. Figure 11 shows data of the valve temperatures at the five different positions shown before. The ordinate shows the temperatures starting from a reference temperature up to +160°C compared to this temperature. The respective temperatures for the plate, the plate edge and the seat contact at the 0° and 180° positions are each summarized under a common y-axis. The abscissa shows the time in an hh:mm:ss format and is showing 5 minutes of measurement. What immediately catches the eye is the different behavior of the various temperature ranges. While the temperature in the center is relatively constant (the fluctuation range here is only a few degrees Celsius), the temperatures in the eccentrically located positions fluctuate significantly.

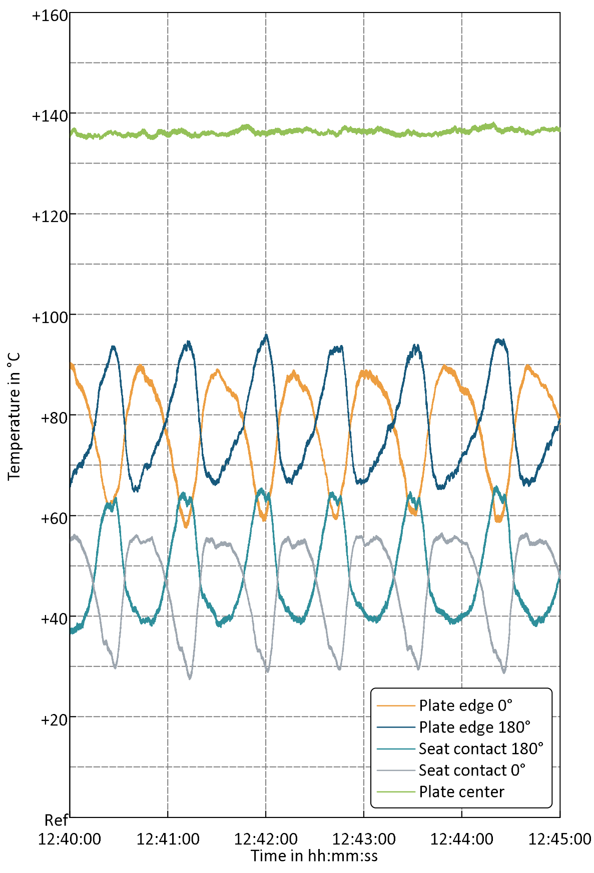

Figure 11: Valve temperature telemetry data

The period of the fluctuations is about 30-40 seconds, the amplitude is about 25 degrees each. Since the temperatures of the 0° and 180° show exactly opposite curves for both axial positions “plate edge” and “seat contact”, it can be assumed that these fluctuations are caused by a rotational movement of the valve. Based on this data, it is assumed that significantly cooler temperatures prevail on the side facing away from the combustion than on the side facing the combustion. An alternative theory could be that the flow velocity between the valves is higher than at the edge, which means that the measuring point is cooled down significantly more when it faces the other outlet valve. Which of these theories is correct, or whether it is a different phenomenon, will subsequently be clarified using CFD simulations.

In general, it can be stated that the temperatures vary not only depending on the position, but also depending on the respective rotation of the valve at this load point. How these temperatures behave during a load change can be observed in Figure 12.

For the plate edge and seat contact temperatures, additionally to the raw signal, a Savitzky-Golay filtered curve has been added to the graph, in order to achieve a better visibility of the load change.

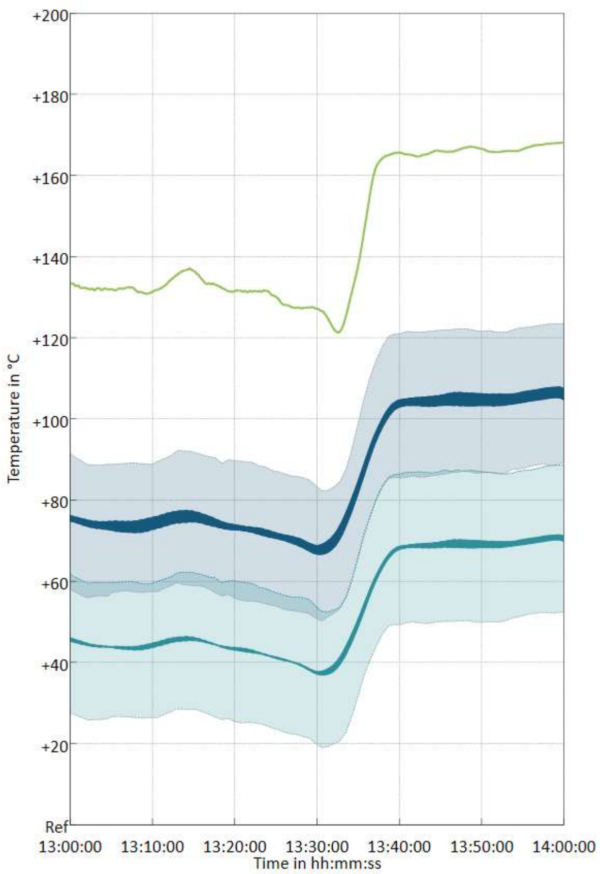

Figure 12: Valve temperatures during load change

The temperature difference between the two measurement positions is almost constant before and after the load change. However, the fluctuations due to the assumed valve rotation are in the same order of magnitude as the temperature increase due to the load change.

The behavior with regard to the fluctuations remains the same, but the level of the measured temperatures shifts. However, the amount of this shift is different for the respective positions, both in absolute and relative terms.

While the valve seat becomes about 20°C (approx. 2.8 %) hotter as a result of the load change, the temperature at the plate edge rises by about 30°C (approx. 3.7 %) and in the center by as much as 40°C (approx. 5 %). One reason for this could be that for solid valves, 75-80 % of the heat flow from the valve to the cylinder head is conducted via the valve seat inserts and only 20-25 % via the valve stem guide [17].

4.1.2 Simulation data

As previously mentioned, these experimental results, in particular the asymmetrical temperature distribution in the valve and the theory of the influence of the valve's rotational movement on the temperature, should be supported with data from CFD simulations.

Figure 13 shows the cross section through an exhaust gas valve. The colormap shows the temperature of the gas after combustion during the exhaust stroke at the time of maximum valve lift.

Despite homogeneous initialization, there are still quite large differences in the absolute values around the valve, which would explain the periodic fluctuations of the valve temperatures. In analogy to Figure 13, Figure 14 shows the flow velocity of the gas at the time of the maximum valve lift in the exhaust stroke.

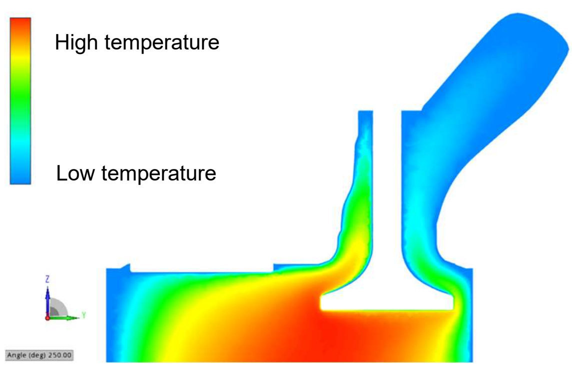

Figure 13: Gas temperature during exhaust stroke

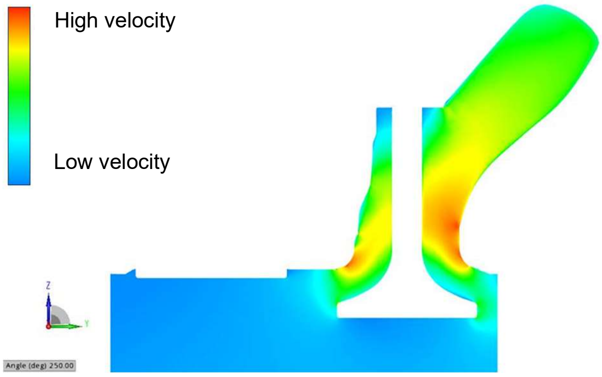

Figure 14: Gas flow velocity during exhaust stroke

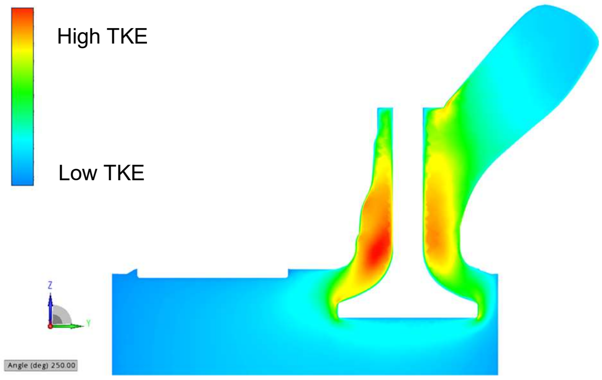

Figure 15: Turbulence kinetic energy during exhaust gas stroke

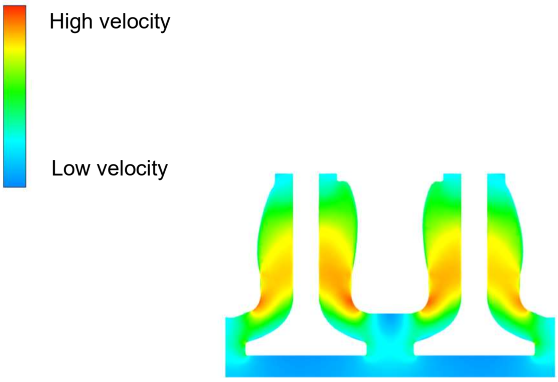

Figure 16: Viewing direction from inlet to outlet

While a kind of wake area with rather low flow velocities is formed on the upper right side of the valve plate, high velocities can be observed on the left side of the valve plate. In addition, the turbulence kinetic energy (TKE) is higher (see Figure 15), presumably leading to higher heat transfer and therefore higher temperatures.

Figure 16 shows the view from the intake towards the valves. The velocity field is largely symmetrical.

However, this does not apply for the temperatures.

As can be seen from Figure 17, the temperature distribution, unlike the velocity distribution, is not symmetrical but, as one would expect, decreases sharply in the radial direction of the combustion chamber. This sectional view therefore also shows an expected hotspot on the side of the valve facing the combustion.

Figure 18 shows a cross section in the plane which is marked in Figure 17 (A-A) looking from fire deck to the piston. It confirms, that the temperature distribution around the valve is largely symmetrical, with one zone of maximum temperatures in the quadrant between the valves and the center of the combustion chamber.

The simulation results appear to confirm the assumptions made on the basis of the experimental results. For the next version of the valve temperature telemetry, a position sensor for recording the current rotational position of the valve is planned in addition to the temperature measurement.

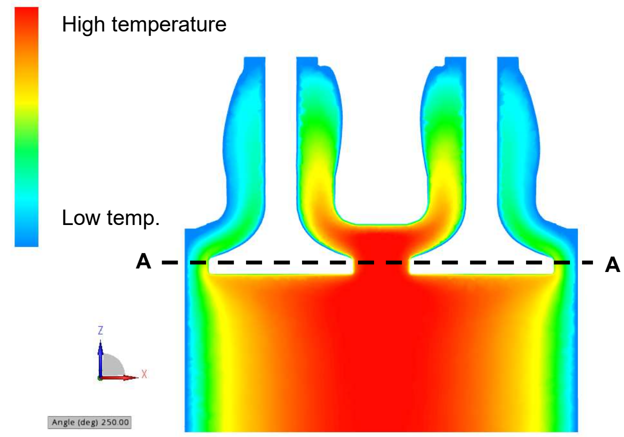

Figure 17: Gas temperature during exhaust stroke viewed from inlet towards outlet

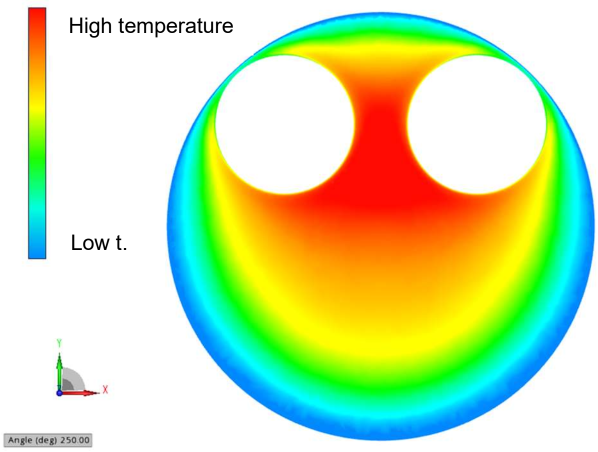

Figure 18: Cross-section A-A view from top to bottom

4.2 Piston ring movement

As mentioned above, the results concerning the axial piston ring movement are already published in [7] and [20] and therefore only be quickly summarized in this paper. In the second part of this chapter, the ring rotation will be shown through an extensive evaluation of the ring groove temperature data.

4.2.1 Axial piston ring movement

A very detailed description of this topic can be found in [7]. At this point, Figure 19 shows for example the movement of the second piston ring to show the results that can be achieved with the help of axial ring movement telemetry. The crank angle in degrees is shown on the x-axis of the graph. The y-axis shows the respective vertical position of the 2nd ring within the ring groove from bottom to top in percent. The measurements were carried out on a 4-stroke engine, whereby one cycle lasts over 720 degrees of crank angle. The graph contains the results of a total of 150 cycles at a 75% load point, with the most frequently occurring curve shown in black. The continuous orange curve shows the mean value, the dashed lines above and below are intended to represent the standard deviation. It can be clearly seen that instabilities of the ring occur both in the working cycle and in the scavenging cycle.

4.2.2 Piston ring rotation

The thermocouples used for monitoring the temperature during the combustion cycle can also be used to track the movement of the first ring gap and, potentially, the second. Localized temperature peaks can be attributed to the alignment of the ring gap with the measured position, as depicted in Figure 20. This graph shows the temperature recordings of 8 positions in the first ring groove.

The positions are evenly distributed around the circumference, resulting in distances of 45° between the measuring points.

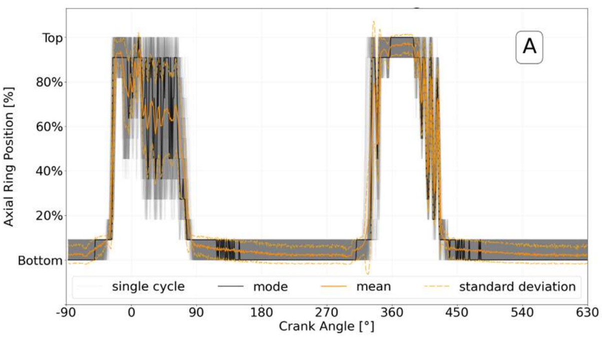

Figure 19: Axial movement of the second piston ring at 75 % load over 150 cycles

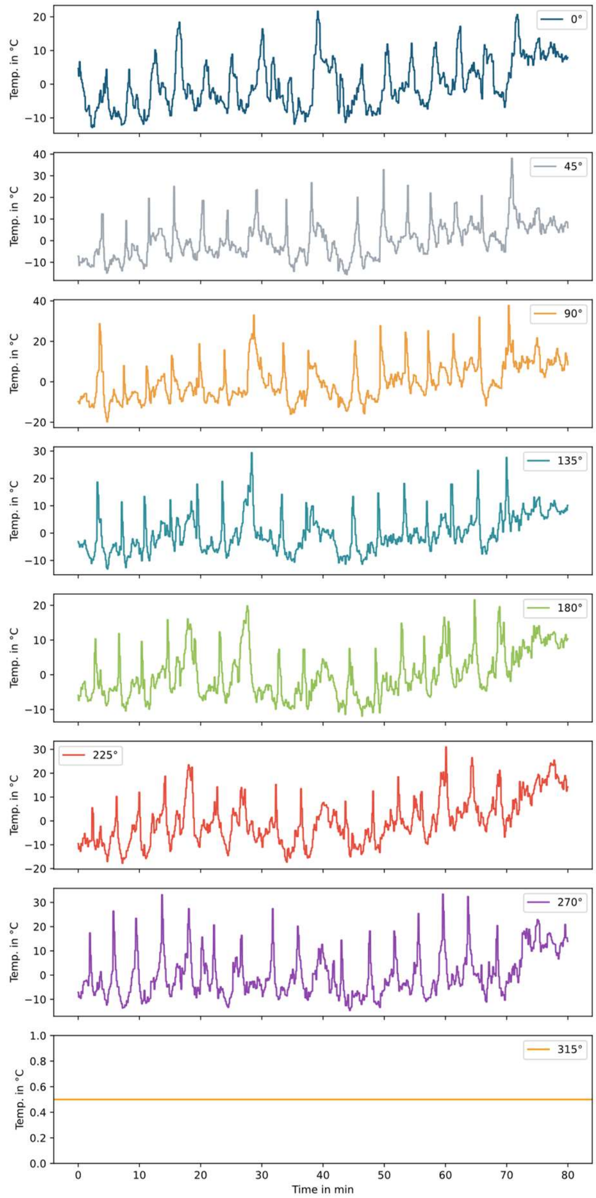

Figure 20: Analysis of the temperature profile of the top-land in a piston during natural gas combustion.

The time in minutes is plotted on the common x-axis. The y-axes show the respective temperature change in relation to the respective mean value.

The temperature sensor in the 315° position has failed, which means that no temperature change can be seen in this graph. One can clearly see recurring peaks at each position, which result from the fact that the ring gap passes the respective measuring point at regular intervals. When this occurs, the temperature rises sharply due to the hot gas flowing past. The average rotational speed of the ring in this sector can be calculated from the time offset of the peaks (e.g. peak 1 at 0° to peak 1 at 45°). The rotational movement of the ring is highly dependent on the combustion conditions,

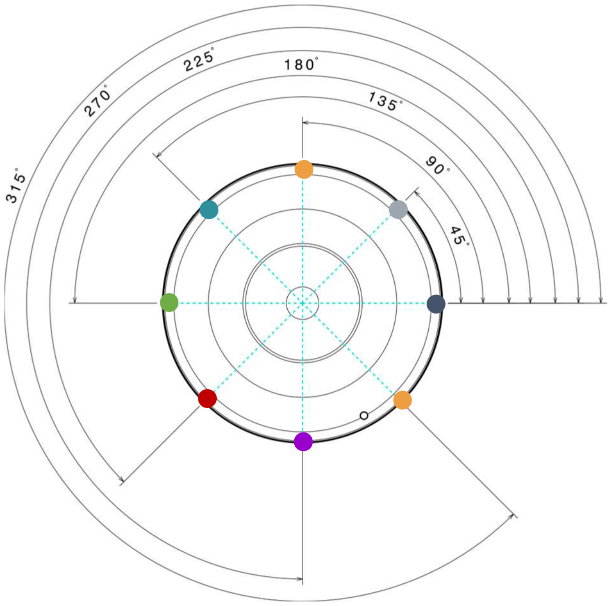

Figure 21: Arrangement of the temperature measuring points in the first ring groove

piston tilt, etc. and it is often linked to high oil consumption. For the sake of completeness, the positions of the temperature measuring points are illustrated in Figure 21. From the peak analysis, it is possible to assume an anti-clockwise movement of the ring gap.

5 CONCLUSIONS

This paper describes the individual steps in the development and design of telemetry systems, not only but especially for large engines. This is necessary to further advance the development of clean combustion engines by providing important insights from inside the engine. This not only serves directly to optimize certain components or assemblies, but also to improve and verify simulation models.

In the design of telemetry systems, certain steps are usually run through iteratively. First, a specification sheet defines exactly which parameters are to be recorded, in what number and at what positions. The next step involves clarifying the available space, the mechanical design, the selection of sensors and measurement technology and the electrical design. As part of the electrical design, it is also important to clarify how the telemetry system is to be supplied with power. As a rule, external power supply via cable, batteries, inductive charging or energy harvesting can be considered. All these design criteria and steps are described using two striking examples. The first example describes the development of a valve temperature telemetry system. The second example is based on the measurement of temperatures and ring movements of a piston. Finally, the results show that the telemetry systems developed in this way provide reliable data from inside the power unit, which was also verified using simulation results. During the valve temperature measurement, it was shown that the rotation of the valve leads to an inhomogeneous, periodically changing temperature distribution in the valve. In the piston temperature measurement, it was shown that the rotation of the piston rings can be measured by evaluating the ring groove temperatures.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AC/ DC: Alternating current / direct current

ADC: Analog to digital converter

IC: Integrated circuit

OHV: Overhead valve engine

PCB: Printed circuit board

PEEK: Polyether ether ketone

PEI: Polyether imide

PGA: Programmable gain amplifier

PLA: Polylactic acid

RX/TX: Receiver/transmitter

TKE: Turbulence kinetic energy

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