In-operando Wear Monitoring on Spark Plugs of Gas Engines

Abstract

Controlled combustion in a combustion engine cannot be achieved without a proper ignition spark at the spark plug. If the status of the spark plug is known, downtimes can be reduced and unnecessary changes avoided. Hence, the goal of this research activity is to develop an ignition voltage and current monitoring system, enabling to keep track of the condition a spark plug is in. Two probes, one for measuring ignition voltage and the other for measuring ignition current, will be developed. These probes will be designed to withstand high ignition voltages without suffering a breakdown. In order to be able to integrate the probes into the system of a gas engine, volume and shape will also have to be considered. Measurement will be approached in a modular set-up, aiming to satisfy the different demands of the industry.

Index Terms — Ignition Energy Measurement

1. Introduction

The present work deals generally with the ignition system of combined heat and power units, short CHP's. CHP's convert the energy of a fuel into heat and electric power. This conversion happens with an efficiency of approximately 85%, as shown in Fig. 1. Different gases can be used as fuel, for example, natural gas, biogas, landfill gas or sewage gas. This means that a CHP can also be used for the disposal of these gases. Another possible usage is island operation or in-net operation for the compensation of net fluctuations, for instance, caused by renewable energies.

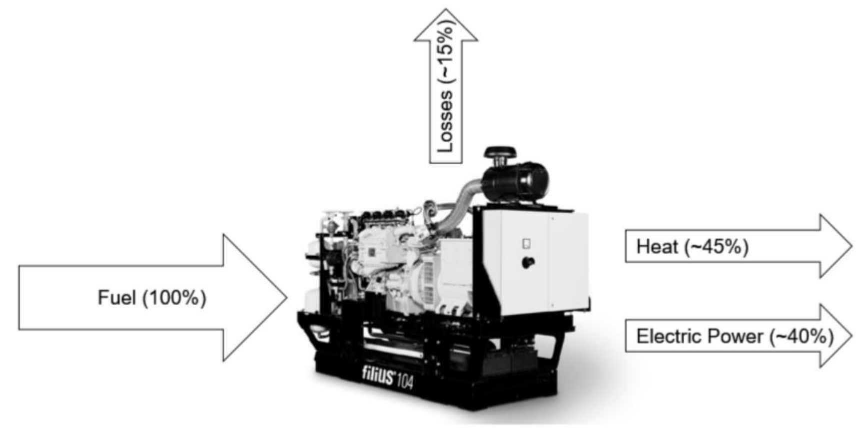

Fig. 1: Combined Heat and Power Unit with Estimated Power Conversion Rates.

A. Problem Statement

In order to initiate the combustion process in an Otto based engine, a mixture of fuel and air must be supplied with energy. This energy is usually given in the form of heat. Reactive radicals react as soon as the energy is fed into the system, enabling combustion, as well as sustaining it for a period of time [1]. Ignition is hence a time-dependent process. The reactants in the combustion chamber induce a first order reaction, based on this a stationary burning flame is achieved or the entire system reacts to the conditions in the combustion chamber. Ignition is always an unsteady process [1]. The external energy is applied by a spark plug, which can be seen in Fig. 2.

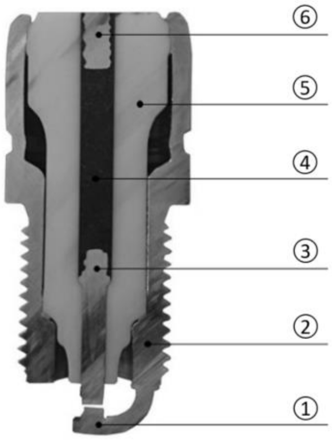

Fig. 2: Cut of a Spark Plug. 1 Mass Electrode, 2 Connection Thread, 3 Middle Electrode, 4 Electrical Conduction Glass Melt, 5 Isolator, 6 Connection Bolt [2].

The middle electrode is often coated with rare metals as iridium to optimize the spark generation. Nevertheless, some erosion occurs to the electrodes during the lifetime of a spark plug as it can be seen in Fig. 3. This leads to a reduced performance of the spark plug and increases the distance between the electrodes.

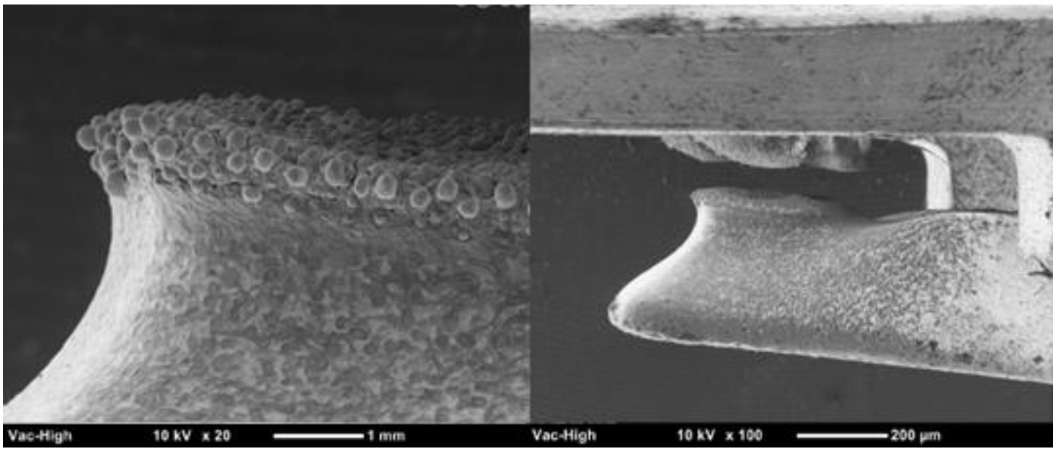

Fig. 3: Scanning Electron Microscope Image of a Spark Plug with Rooftop Electrode and Spark Erosion. Image taken with 20x and 100x Magnification [2].

B. Economical Potential

In Germany, approximately 6,500 biogas engines are installed. These engines need approximately 200 thousand spark plugs every year. For natural gas, approximately 3,000 engines are installed, which need 60 thousand spark plugs every year. The higher demand for spark plugs for biogas engines is due to the more aggressive behavior, coming from more accompanying substances. Also, more turbulence of the combustion is needed for theses CHP's. The global production of spark plugs for CHP's is estimated to between 1.2 and 1.5 million per year. With the average price of about 240 € per spark plug, there is certainly some economic potential in determining the status of the spark plug. In general, the plugs are replaced after a defined time, to avoid breakdowns and possible damages on the engine. Therefore, at the moment of change, the spark plugs could still be working. It has also be mentioned that the spark plugs will not age constantly in an engine, for example, are the cylinders in the middle of the engine hotter than the ones on the end of the engine.

2. Fundamentals

A. High Voltage Generation

In order to achieve an ignition spark, high voltage is required. Even though there are different possibilities for an ignition system to generate this voltage, the traditional ignition coil is still the most frequently used method. A simplified overview of an ignition system is given in Fig. 4. The switch shown in the figure is closed during operation. In the moment, where the regarding spark plug shall initiate the ignition, the switch opens. The high voltage will be generated by the coil, which has a high transmission ratio from the primary to the secondary side. The monitoring of the ignition energy shall happen in the area between the coil and the spark plug.

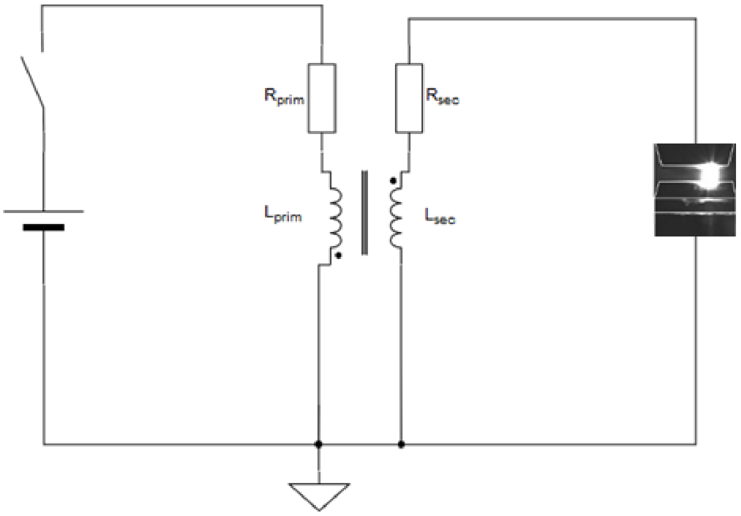

Fig. 4: Simplified Overview of a Standard Ignition System Consisting of Ignition Coil, Circuit Breaker, and Voltage Sourece on the Primary Side as well as Spark Plug on the Secondary Side.

B. Spark

When a specific voltage is reached, a spark will occur between the electrodes and the voltage will break down, which can be seen in Fig. 5. The next phase is the discharge, in this phase, the spark is active between the electrodes. Afterwards, the spark expires and a swing-out can be monitored. The images in Fig. 5 are taken with a high-speed camera at the test bench, which will be introduced later. The images correspond with the chronological sequence of the voltage. The brightest spark at the moment of the break down indicates the high power at this moment.

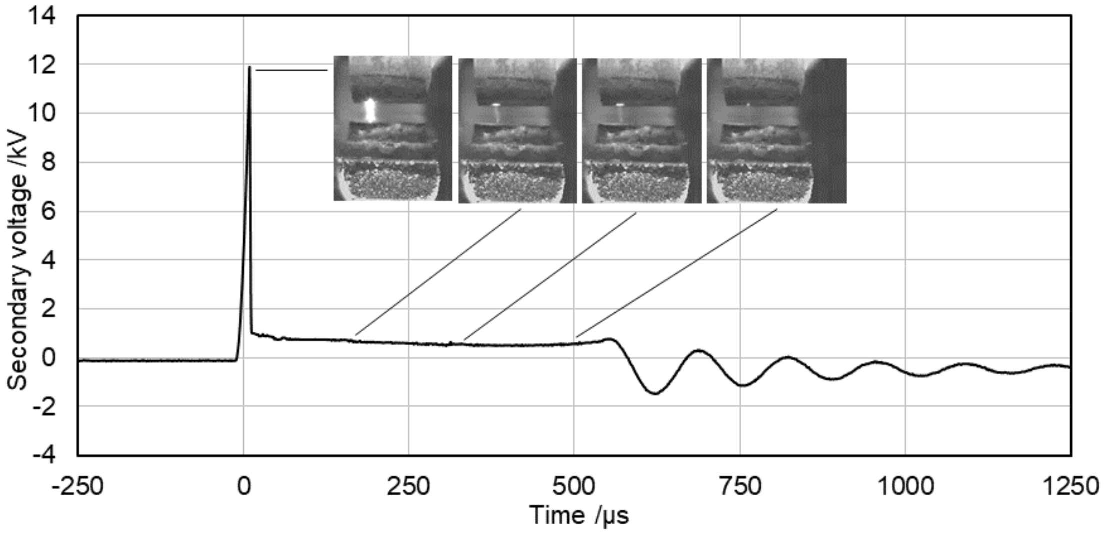

Fig. 5: Typical Development of the Secondary Voltage with the Chronological Corresponding Images of the Spark, Captured with a High Speed Camera.

Generally, a spark is defined as a flashover between two surfaces caused by a high electrical voltage. This gas discharge is based on the flow of electrical current through a gas-filled room. Freely available charge carriers in the gas between the electrodes are thus accelerated, the structure of the gas between the electrodes begins to change as the voltage rises. The thereby generated ionization causes charge carrier avalanches. These avalanches result in the final breakthrough of the charge.

The voltage required for the spark to breakthrough depends on various factors, including pressure, type of gas, or the distance between the electrodes. The relation between these factors is described in Paschen's law.

At this point, it shall also be noted that the breakdown voltage has a random parameter range. It is hence not possible to determine the exact value, which also means that a repetition of the experiment will never yield the exact same value [3].

C. Paschen's Law

The Paschen law is named after Friedrich Paschen who conducted influential studies on the electrical breakdown in 1889. For his most famous experiments, he used two parallel plates with a defined distance *d* and applied a voltage to them. The voltage was increased until a certain threshold value, breakdown voltage U_{bd}, was achieved where the electrical breakdown occurred and a high current could finally pass. Paschen identified the voltage as the product of pressure *p* and gap length or distance *d* [4]. Paschen's law is defined in Eq. (1) [4, 5]

$$U_{bd} = \frac{\mathrm{B}pd}{\mathrm{C} + \ln(pd)} \tag{1}$$

where

$$\mathrm{C} = \ln(\mathrm{A}) - \ln[\ln\left(1 + \frac{1}{\gamma}\right)] \tag{2}$$

A and B are constants dependent on the gas. The constants are determined empirically. Depending on the source, these values may vary. The retroactive effect constant γ is a material constant, which depends on the material of the electrode and the used gas. Based on the equations before, the height of the breakdown voltage regarding the distance between the electrodes can be calculated. These calculated values are shown in Fig. 6. With this knowledge, it is possible to determine the electrode distance depending on the measured voltage, which thus leads to a conclusion about the spark erosion aging effect.

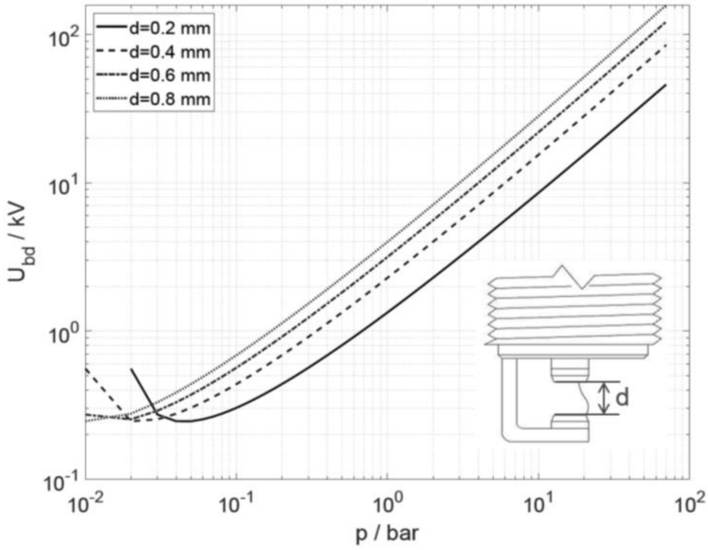

Fig. 6: Comparison of Different Distances *d* regarding Paschen's Law. The Values are Calculated for Air.

D. Spark Plug

The before described spark will in an engine be provided by a spark plug. As the environment, in which the spark plug is used, is usually one of extreme temperature, pressure, and other forces, it has to be resistant in a number of different ways. Smooth operation can only be achieved if the spark plug can withstand all the forces that are at play in a gasoline engine combustion chamber. Therefore, it has to fulfil several different characteristics that can be defined as follows [6]:

- Electrical: The spark plug has to achieve a high voltage transmission of up to $U_{spark\ plug}$ = 45 kV. This voltage has to be isolated and a breakthrough has to be avoided. The ability to withstand the dielectric burden in the engine has to remain unchanged throughout its lifespan.
- Mechanical: The spark plug has to seal the combustion chamber. In order to achieve proper sealing, the high pressure in the combustion chamber has to be considered, as has the power of the screwing.
- Thermal: A good heat conductivity is important for the spark plug to be able to withstand the small thermal shock at each combustion cycle. This is also necessary to avoid an unwanted inflate at a hot spark plug.
- Electrochemical: The spark plug furthermore has to withstand erosion and is expected to prevent deposition on the isolator, which would endanger smooth operation.

Over the years, the fundamental design of a spark plug has hardly changed. The working principle has basically remained the same ever since its invention by Robert Bosch in 1902 [7]. Recently, the demands on the spark plug have, however, become increasingly complex. This has necessitated some minor changes in shape or material [6].

A spark plug experiences various aging effects over the course of its operating life. These effects also have an impact on its working behavior. Aging of a spark plug can go so far as to induce a total collapse. Such a sudden collapse can cause unburned fuel to remain in the exhaust tract and lead to backfire. Major damage to the engine can also occur if parts of the spark plug break off due to wear and fall into the combustion chamber.

One such harmful aging effect is spark erosion. This refers to the interaction of discharge plasma with the surface of the electrode, as shown in Fig. 3.

Spark erosion, can, for example, increase the distance between electrodes and, consequently, also require increased voltage to generate a spark. The required ignition voltage can increase up to 20 %. By adjusting the distances between electrodes, this can be counteracted, yet only to a certain extent. This is because there are definite limitations regarding the accessibility of the mixture required for ignition and consequent combustion [6].

3. Methods

To determine the energy of the ignition, the measurement of the voltage and the current will be separated into two probes. This modularity ensures higher flexibility. The final solution shall fit for existing engines as a retrofit as well as for new engines. A stand-alone device will also be developed. This device enables also communication to the existing system architecture. The ignition system shall be influenced as less as possible by the measurement. The final probes have to withstand the high voltages of the coil. The developed solutions shall also serve a valuable price/performance ratio. Fig. 7 shows the top view of a six-cylinder CHP where the mounting conditions can be seen.

Fig. 7: Top View of a six Cylinder CHP. Upper Side of Image: Ignition Coils Mounted. Lower Side of Image: Cylinders with Spark Plugs [8].

There are several methods available for the high voltage and current measurements. Due to the complexity, the power consumption and the possible volume of the measurement the decision is made for the capacitive voltage divider for the voltage measurement. Integration into the existing system is considered to be feasible. Similar reasons occur for the current measurement. Therefore, the decision is taken for the inductive coupling. Both measurements will be held separate to ensure modularity and thus it is possible to please various demands of different customers.

4. Results

Both probes have a connection plug, which can be connected via a coaxial adapter cable. With this cable a visualization on an oscilloscope is possible.

A. Voltage Measurement

To ensure a measurement independent from the frequency of the signal, a compensation has to be conducted. The circuit for this task can be seen in Fig. 8. The resistors R_1 and R_2 have values which ensure for both RC-parts the same time constant. R_3 avoids reflections in the connected cable. The value for R_3 depends on the impedance of the cable and R_2.

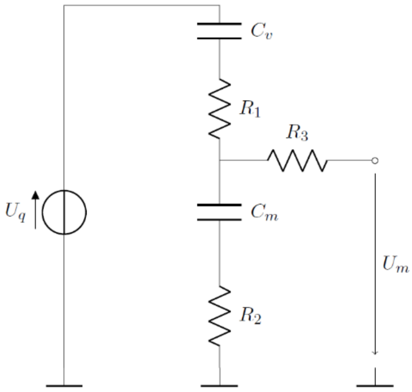

Fig. 8: Capacitive Voltage Divider, Frequency Independent.

After some steps of evolution in development, the final version of the voltage probe is produced. The manufactured probe is shown in Fig. 9. A significant reduction of the volumetric size is achieved from the first approach to the final solution.

Additional to the coaxial adapter cable it is possible to connect the probe to a stand-alone electronic device. This device is able to display the breakdown voltage. Due to the demands of the industry, this is, at the moment, only possible for the voltage measurement. However, the integration of the current measurement and thus also the calculation of the energy is possible with a few modifications and will be conducted in future.

Fig. 9: Voltage Probe Assembled with Plug [9].

For the stand-alone device a printed circuit board, short PCB, is manufactured. This PCB is shown in Fig. 10. The device is supplied by a battery and a buck converter. Furthermore, a microcontroller *XMC1404* from *Infineon* is mounted to process the signal and control the display. The display is connected via the pin header *P1*. To ensure an easy connection, the pin header has the same size as the header of the display. The hole PCB has also the same geometrical size than the display. The pin header *P5* is routed to an analog to digital converter of the microcontroller. At this header, the voltage probe is connected.

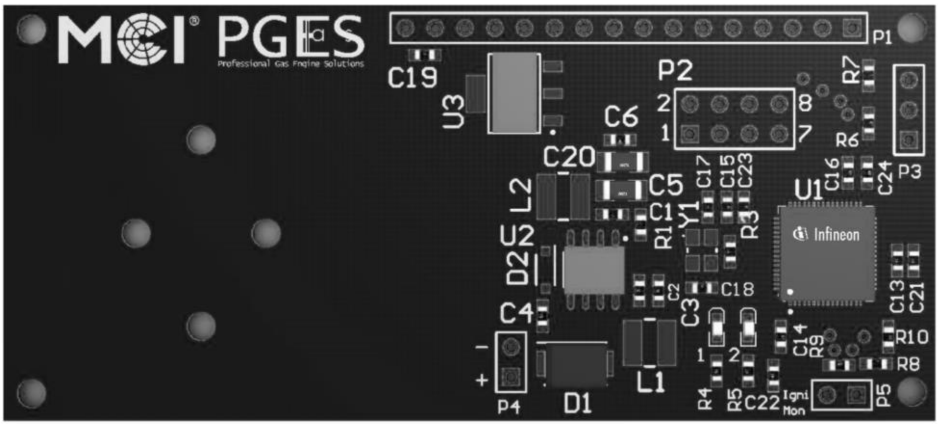

Fig. 10: PCB for the Voltage Monitoring. Main Parts: Microcontroller for Signal Processing and Control of the Display, Voltage Supply [9].

The software of the microcontroller monitors the signal on the input pin. This signal is converted on an ADC. If the measured signal is U > 5 kV, the start of a voltage peak is recognized. This initializes the recording of the following 2,000 measurement points. As the samples are recorded, the logging ends and the data is searched for the maximum value. This peak value is saved. This procedure is repeated five times. After five peaks have been saved, the results are averaged. This is because the information about several peaks is more significant than one measurement alone. Furthermore, it would not be possible to read the data of every single ignition on the display. The number of collected peaks can be changed according to user preference. After the averaging, the final value is shown on the display. The flowchart of the explained procedure is presented in Fig. 11. The software is programmed in C.

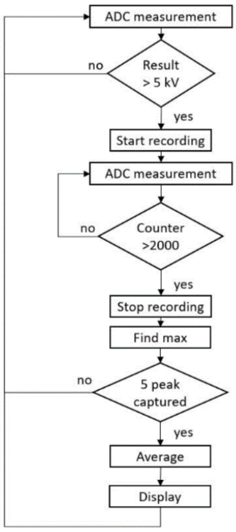

Fig. 11: Software Flowchart for Break Down Voltage [9].

B. Current Measurement

As the behavior of different ferrite materials can strongly vary, a few samples were ordered from different manufacturers. The aim of comparing the samples is to determine the material with the highest possible linearity over a wide frequency range.

From the chosen material a coil is build. For this reason, a wire is wound around the core. To determine the inductance of the coil an LR-low pass filter is build up with the used components. Using Eq. (3), the inductance can be calculated.

In order to decrease the possibility of measurement errors, the voltages are measured across several frequencies. The average of calculations is taken as the final value, yielding L_m = 5.9 mH as the result for this coil.

$$L = \frac{R\sqrt{(\frac{U_i}{U_o})^2 - 1}}{2\pi f} \tag{3}$$

By means of the created coil, the measurement is implemented as shown in Fig. 12. As a measurement resistor R_m = 100 Ω is chosen. On the one hand, with a higher resistor, the current flow would be limited too much. On the other hand, with a smaller resistor, the voltage drop on the resistor would be too low compared to the noise of the oscilloscope probe.

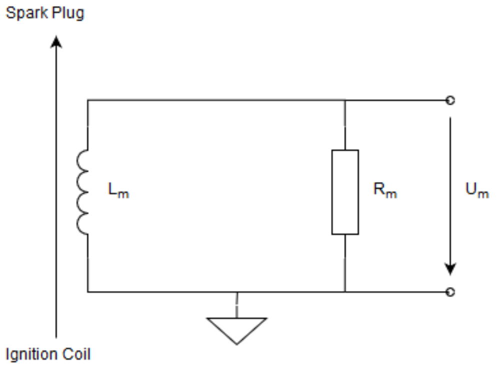

Fig. 12: Setup of the Current Measurement.

To calculate the measured current the equation of an LR parallel filter circuit is used. The measurement circuit does not exactly represent the filter, but during measurements, good results are achieved with this calculation, Eq. (4).

$$i_{total}^2 = i_R^2 i_L^2 \tag{4}$$

Due to the coupling factor of the inductive current measurement, it is necessary to amplify the result. Reference measurements are showing that this amplification changes over the range of different pressures at the spark plug. At higher pressures, less amplification is necessary to reach the result of a reference measurement. Because the pressure is not an available value, the amplification connected to the breakdown voltage is from the voltage measurement. As discussed before, the breakdown voltage is related to the pressure. Additionally, a lowpass filter is implemented to reduce peaks in the measurement, which exceed the reference measurement.

C. Energy Calculation

The power is calculated by multiplying the voltage by the current. To obtain the energy of the ignition process, the power has to be integrated over time.

D. Measurements on the Test Bench

The test bench is specifically built to investigate the behavior of spark plugs in gas engines. It is designed to simulate different pressures at the electrodes. The spark plug is mounted in a pressure chamber by screwing. The chamber has a viewing window to enable observation of the spark during operation. A second window is installed at the ground of the pressure chamber to illuminate its interior. The pressure and temperature in the chamber are monitored, digitized, and recorded on a computer. The computer is set up in another room to avoid possible hazards arising from the high pressures. As test gas, synthetic air from a bottle is used. A pressure regulator is mounted on the bottle to allow the pressure for the system to be adjustable. The test bench also includes a mass flow meter and a controlled outlet to simulate the blow of a spark. The concept of the test bench is shown in Fig. 13.

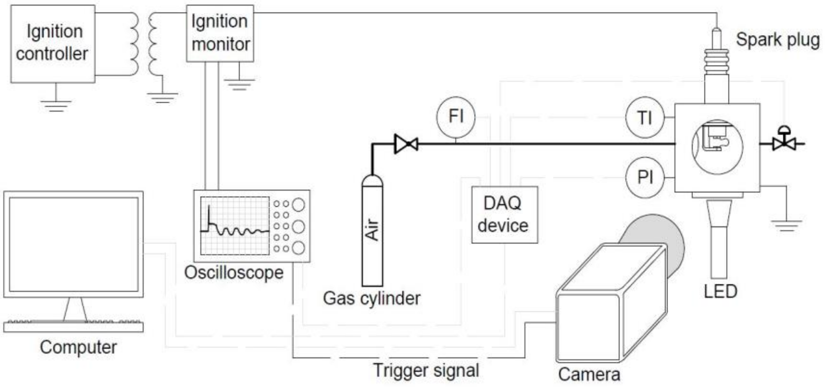

Fig. 13: Concept of the Test Bench [2].

The installed ignition coil has an external secondary mass connection. This enables reference measurement of the ignition current. Therefore, a shunt resistor is integrated at the secondary mass connection.

The relevant signals are recorded by an *InfiniiVision DSOX2024A* oscilloscope by *Keysight*. Both current signals are taped using probes of the *Keysight N2842A* type. The collected data will be processed and illustrated by *MATLAB/SIMULINK*. This data processing works automatically with the created scripts and files.

The names of the spark plugs that will be used are internal indicators. This is because some of them are prototypes and not yet available on the market.

As discussed in previous sections, the breakdown voltage can be calculated and the theoretical calculation be compared with the actual measurements. For the calculation and subsequent comparison, the pressure and the distance between the electrodes has to be known. The electrode distance is difficult to measure at a ring gap spark plug. For the *ERS5355*, d = 0.3 mm is determined as an approximate value. The material of the spark plug electrodes is not exactly known. The comparison is shown in Fig. 14. This illustrates that the measured U_{bd} is slightly below the value calculated for d = 0.2 mm. Several explanations are thinkable. Despite the deviation of the measured and calculated results, it can be seen as a good sign for the spark plug to have a lower breakdown voltage. This is because it reduces aging effects and ensures a longer lifespan.

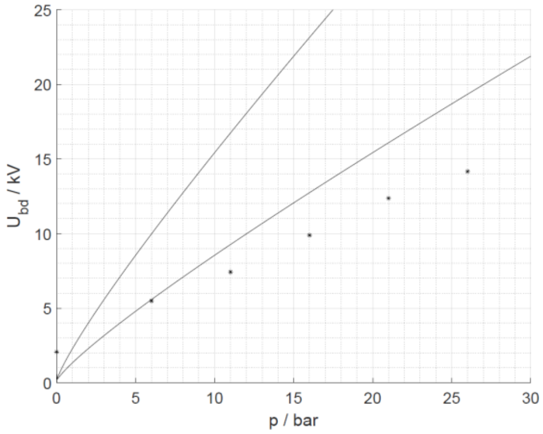

Fig. 14: Correlation of Paschen's Law and Break Down Voltage of the *ERS5355* Spark Plug. Lower Solid Line: Calculated Breakdown Voltage with d=0.2 mm, Upper Line: with d=0.4 mm. Dots: Measured Breakdown Voltages.

With the developed hardware it is now possible to measure the voltage and current of the ignition. For every measurement, 20 signals are taken and averaged. This leads to a more meaningful result, because, as before already described, every spark is unique. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the signal of voltage measurement. Therefore, the same spark plug is tested at various pressures. It can be seen that the measurement at 0 bar relative is different than the others. This is normal behavior and is reproducible, but the exact reasoning needs further investigation. In **Fehler! Verweisquelle konnte nicht gefunden werden.** are the current signals displayed of the same measurement as for the voltage. The reference measurement differs from the measurements with the *Ignitionmonitor*. This is due to the thermal noise of the measurement with the oscilloscope probe. The same behavior would happen before the peak, however, the starting point of the peak is taken from the voltage measurement and every value of the current measurement before the peak is set to zero. With the voltage and current, the energy can now be calculated, the signals are shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The decrease of the signals measured with the *Ignitionmonitor* is due to the offset of the current measurement. However, the top of the signal corresponds to the reference measurement. It has to be mentioned, that the controller of the ignition system defines the energy and the current. Therefore, the variance is not significant at various pressures. This means also, that the voltage measurement is the most meaningful one in regard to a later on lifetime prediction.

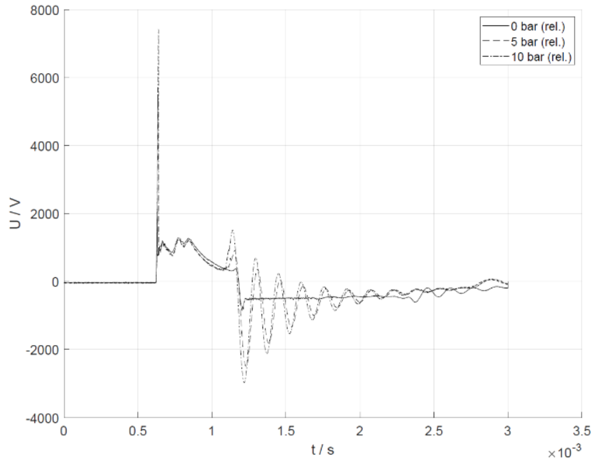

Fig. 15: Voltage Signals at Various Pressures.

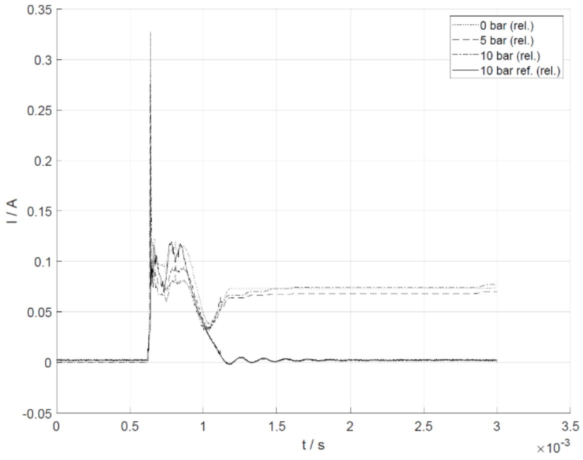

Fig. 16: Current Signals at Various Pressures with Reference Measurement.

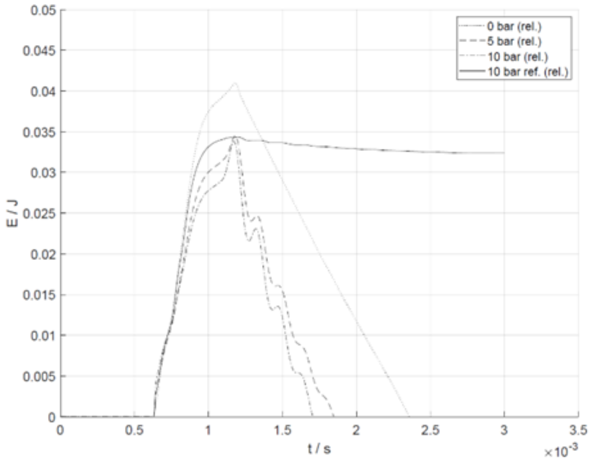

Fig. 17: Calculated Energies at Various Pressures with Reference Calculation.

5. Conclusion

It has been shown that it is possible to create a simple and relatively inexpensive ignition energy measurement system. The developed devices can capture both, the voltage and the current of standard gas engine ignition systems. They can also be used on a variety of different ignition coils.

Despite the very positive results obtained in this initial step of development, there is still a lot of work to be done. The electronics of the voltage measurement, for example, need further development. The display and the PCB will still have to be adapted in a housing suited for the industry. The evaluation unit shall be extended to record the current as well as the energy. Furthermore, the design of the setup has to be adapted in a modular way, so that it is more flexible and fit to meet the costumers' different requirements. Another aspect that could be improved is to work on finding a method to visualize the full graphs rather than just the height of the peaks measured.

Further improvement of the electronics shall provide the possibility to integrate the recorded data into the engine operating system. The controller of the plant in which the system is used could then shut down the engine in case of misfires and prevent the engine of further damages. One way to implement this communication feature could be by applying a CAN protocol. A typical protocol standard is *J1939*. Other options have to be evaluated, to ensure a wide range of possible usages. It also has to be noted that during interpretation of the results, it has been found that the energy released by the spark plug is not the most characteristic value in determining its state.

To determine the wear of a spark plug is an observation of the breakdown voltage suitable. Regarding Paschen´s law depends this value on the pressure and the distance between the electrodes. Therefore increase the voltage which is necessary for a breakdown with increased wear.

Another approach is the observation of the oscillation in the voltage signal. This oscillation is reasoned by the resonant circuit consisting of the inductance of the coil and the gap of the electrodes which act as a capacitor. With increased wear will the surface of the electrode and therefore the capacitance change.

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