2.2 Test Rig for Fundamental Investigations of Ignition System Characteristics under Severe Flow Conditions

Anton Tilz, Georg Meyer, Constantin Kiesling, Gerhard Pirker,
Sebastian Salbrechter, Andreas Wimmer

Abstract

Stationary spark ignited (SI) gas engines play an important role in decentralized energy supply concepts. To achieve further improvements in efficiency and to decrease emissions, engine operating strategies with very lean air-fuel mixtures and high turbulence levels are required. However, these severe conditions have a significant impact on the inflammability of the mixture and compromise combustion stability. Reliably igniting the mixture and keeping cycle-to-cycle variation of the combustion process at a low level is challenging and requires deeper understanding of the fundamentals of the ignition process. The electric arc, which transfers the electric energy to the air-fuel mixture and initiates the inflammation, plays a central role in the ignition process. Thus, the paper at hand presents a test rig that was developed for detailed investigations of electric arc behavior under flow conditions similar to those in spark ignited large gas engines.
The test rig consists of a closed loop flow circuit. Flow velocities at the spark plug up to 30 m/s, pressures up to 60 bar and temperatures up to 80 °C can be achieved under non-combustible conditions. The centerpiece of the test rig is the test cell, which provides excellent optical access from three sides for high-speed imaging of the arc without disturbing the flow field at the spark plug. A sufficiently long stabilizing path upstream of the test cell guarantees defined and fully developed turbulent pipe flow conditions at the spark plug. Sophisticated post-processing algorithms were developed that automatically extract relevant data from the high-speed images (e.g., arc length) and compare the information with electrical signals such as current and voltage on both the primary and secondary sides of the electronic ignition system. The results provide a deeper understanding of the ignition process and serve as basis for model validation. Finally, measurement results of a pressure variation are presented and discussed. The results show greater arc stretching and increased cycle-to-cycle variation in arc length at higher pressures.

Kurzfassung

Stationäre Großgasmotoren mit elektrischer Funkenzündung stellen eine wichtige Säule für die dezentrale Energieversorgung dar. Zur Steigerung des Wirkungsgrads sowie zur Absenkung der Emissionen kommen dabei immer höhere Luftverhältnisse bei gleichzeitig gesteigerten Turbulenzniveaus im Brennraum zum Einsatz. Diese Betriebsbedingungen beeinflussen jedoch die Entflammbarkeit des Gas-Luft-Gemisches und beeinträchtigen die Verbrennungsstabilität. Die zuverlässige Entflammung des Gemisches und die Erreichung geringer zyklischer Schwankungen beim Verbrennungsprozess stellen somit eine Herausforderung dar und setzen ein tiefgehendes Verständnis des Zündprozesses voraus. Eine zentrale Rolle spielt dabei der elektrische Funke, der die elektrische Energie an das Gas-Luft-Gemisch überträgt und den Zündprozess einleitet. Zur detaillierten Untersuchung des Funkenverhaltens unter motornahen Bedingungen wurde daher ein spezieller Prüfstand entwickelt, der in der vorliegenden Publikation vorgestellt wird.

Der Prüfstand besteht aus einem geschlossenen Kreislauf, in dem Strömungsgeschwindigkeiten an der Zündkerze von bis zu 30 m/s, Drücke bis zu 60 bar und Temperaturen bis zu 80 °C unter Verwendung nicht brennbarer Gase realisiert werden können. Kernstück des Prüfstandes bildet eine Testzelle, welche zur Aufzeichnung des Funkenverhaltens mittels Hochgeschwindigkeitskamera exzellente optische Zugänglichkeit von drei Seiten her bietet, ohne dabei die Strömung an der Zündkerze zu beeinflussen. Eine ausreichend lang dimensionierte Einlaufstrecke stromaufwärts der Testzelle sorgt dabei für eine definierte und voll ausgebildete turbulente Rohrströmung an der Zündkerze. Eigens entwickelte Auswertealgorithmen dienen zur Quantifizierung der Messdaten aus den Hochgeschwindigkeitsaufnahmen und zur Einbeziehung der elektrischen Signale von der Primär- und der Sekundärseite des Zündsystems. Die Messergebnisse erlauben ein tiefgehendes Verständnis des Zündprozesses und dienen überdies zur Validierung eines Zündungsmodells.

In der vorliegenden Publikation wird anhand einer Parameterstudie gezeigt, dass die Anhebung des Drucks an der Zündkerze bei konstanter Strömungsgeschwindigkeit zu einer größeren Funkenstreckung sowie zu höheren zyklischen Schwankungen der Funkenlänge führt.

1 Introduction

Spark ignited (SI) large gas engines are important for decentralized energy supply concepts and will continue to be so in the future, cf. [1] [2]. Increasingly stringent emission regulations along with the quest for greater engine efficiency present challenges in the design of the combustion process. To meet these requirements with gas engines, there is a trend towards leaner air-fuel mixtures and higher mean effective pressures, cf. [1] [2] [3]. Consequently, the range for stable engine operation between knocking and misfiring is significantly reduced, cf. [4]. Since robust engine operation under these difficult boundary conditions must be ensured, a central topic of research is combustion stability, cf. [2] [5]. The ignition system is a key component in reducing cycle-to-cycle variations because it initiates combustion with an infant flame kernel that turns into a stable flame front, cf. [4] [5]. Research focuses on improving the ignition process and developing alternative ignition systems, cf. [2] [4] [6] [7] [8] [9]. Despite the availability of alternative ignition concepts, the concept with electric gas discharge at a spark plug remains the standard in production engines thanks to its robustness and reliability as well as its cost-effective design, cf. [2] [10].

The ignition system transfers electrical energy to an ignitable mixture and initiates combustion with the help of an electric arc, which raises the local gas temperature above a level favorable for the formation of an infant flame kernel, cf. [11] [12] [13]. Flow and thermodynamic conditions at the spark plug greatly vary depending on the engine design as well as on the operating conditions, e.g., lean or rich, homogenous or stratified air-fuel mixture, low or high charge motion and low or high pressures. Since the electric arc is a conducting region between the electrodes and part of the electric circuit, these local conditions at the spark plug have a significant impact on electric arc behavior and on ignition system performance, cf. [12] [13] [14]. Reliable ignition of the air-fuel mixture under all conditions is very challenging. Since the ignition process is one possible cause of irregular combustion, e.g., misfire and large cycle-to-cycle variability, it is important to investigate the effect of electric arc behavior on the combustion process, cf. [5] [15].

There are two main advantages to conducting detailed research into electric arc behavior at spark plugs. First, the ignition process in large spark ignited gas engines can be better understood by analyzing the details of spark discharge at extreme conditions comparable to those in large gas engines. Second, it enables the improvement and validation of the capabilities and accuracy of ignition and combustion simulation models that assess SI engine concepts without engine test beds. LEC GmbH is in the process of developing a detailed ignition model for 3D CFD simulation that consists of several submodels including an electric network model and an arc model, cf. [16]. Arc behavior and flow-feedback on the ignition system are thus an important part of the model that needs to be validated over wide operating ranges.

The innovative test rig presented in this paper is designed to facilitate a detailed investigation of electric arc behavior under cross-flows at a spark plug typically used in gas engines. The following two sections provide a short summary of the fundamentals of the arc test rig, the arc test rig requirements and the methodology; for more detailed information, see [13].

2 Arc Test Rig Fundamentals and Requirements

This section provides a brief introduction into the fundamentals of electric gas discharge. Based on these fundamentals, requirements for a test rig suitable for addressing key research topics are deduced.

2.1 Fundamentals

Figure 1 presents a schematic circuit model of a modulated capacitive discharge ignition (MCDI) system, cf. [2] [12] [13], an ignition system common in large gas engines. This system was installed on the arc test rig described in this paper. Activation of the ignition system transfers the energy stored in a capacitor on the primary side to the secondary side via an ignition coil. As long as the gap between the spark plug electrodes is insulating, the voltage across the electrode gap rapidly increases until breakdown occurs. In the first short phase of breakdown, the energy stored in the capacitors on the secondary side is released at time scales on the order of microseconds. In the glow or arc phase that follows, electric discharge occurs as a result of the transfer of energy from the primary capacitor through the ignition coil; a distinct arc column is established at time scales on the order of several microseconds and is sustained up to one millisecond by the energy transferred from the primary side.

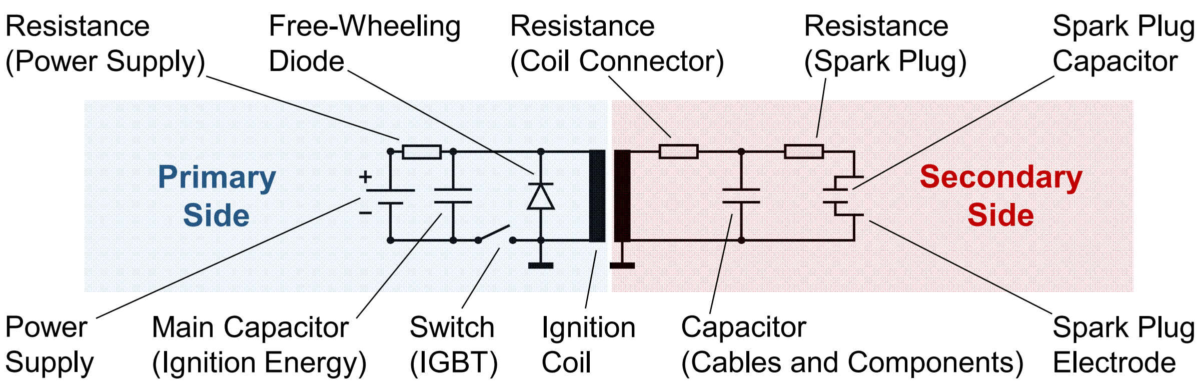

Figure 1: Schematic circuit model of a MCDI system

In this phase, the spark power is influenced by modulating a switch on the primary side; this is the core principle of MCDI technology. The flow field at the spark plug has approximately one millisecond during which it interacts with the arc column. Therefore, the state of the arc that acts as electric impedance in the secondary circuit greatly depends on the prevailing thermodynamic conditions and flow situation at the spark plug.

2.2 Requirements

An investigation of arc behavior and its impact on the transfer of energy from the electronic ignition system to the gas necessitates a study of the electric arc under well-defined, stable oncoming flow conditions at pressures and flow velocities similar to those in an engine and in an otherwise inert gas atmosphere. Three main parameters must be examined in a test rig:

- Flow velocity at the spark plug
- Ambient pressure
- Ambient temperature

Any observation of the influence of flow motion requires a well-defined, directed and steady oncoming flow. The velocities at the spark plug electrodes should be able to be adjusted from 0 – 30 m/s; this upper limit was derived from engine simulation results. The spark plug orientation should be as flexible as possible in order to ascertain the influence of the main flow direction on the arc behavior. Since load changes in the engine result in a wide variety of pressures at ignition timing, the pressure should be variable over a large range during experiments, cf. [16]; the target is a pressure range of 1 – 60 bar. It is expected that the sensitivity of the electric properties of the arc column to changes in ambient temperatures (in contrast to breakdown properties) is less than to changes in pressure, cf. [13] [25]. Thus, a temperature range of 25 – 100 °C is envisioned in order to avoid disproportionate effort with respect to the test rig design.

The test rig must make it possible for different non-combustible gas atmospheres to be obtained in order to isolate electric arc behavior from the actual combustion. The focus is placed on air, a main component of inflammable mixtures in gas engines, yet it should be possible to use other non-combustible atmospheres as well. Equally important is the proper integration of the ignition system and the types of spark plugs used in real engines into the test rig. Furthermore, specialized spark plug geometries such as spark plugs with two separate electrodes must be accommodated. High-speed optical evaluation of the electric arc behavior requires good optical access to the spark plug electrodes. Optical access from multiple angles is desirable to obtain an impression of the three-dimensionality of the arc evolution. Since this optical information has to be linked to the electronic feedback of the electric arc in the ignition system of the same spark event, a sophisticated measurement setup is necessary that can record fast measurement signals such as current and voltage on both the primary and secondary sides.

2.3 State-of-the-Art

Prior to the development of the arc test rig, a detailed literature study was carried out to determine the characteristics of existing test rig designs and their limitations in arc behavior investigations. The state-of-the-art systems are summarized briefly below.

Several studies described investigations of arc behavior in optically accessible constant volume pressure chambers, some of which were able to achieve comparatively high pressures and/or temperatures but under quiescent flow conditions, cf. [17] [18] [19] [20]. Research engines with side chambers facilitate high flow velocities but do not obtain defined steady-state flow conditions at the spark plug, cf. [21] [22] [23]. In test rigs where spark plugs lack a housing or in specific open chamber concepts (gas flows through the chamber), the flow velocities are achieved with a nozzle or a connection to inlet piping upstream of the spark plug. However, these systems do not provide high temperatures and high pressures, cf. [17] [24] [25] [26] [27] [28]. A setup described in [29] can obtain high gas temperatures up to 1200 °C at mass flow rates up to 2.15 kg/s but at pressures up to only 5 bar. A test rig consisting of a closed loop flow circuit with an integrated chamber for the spark plug is described in [30] and [31]. Because of its compact design, the length of the inlet before the spark plug is comparatively small, which may impede the achievement of defined flow conditions at the spark plug due to induced secondary flow. All test rigs except [18] [19] [20] [21] [22] [23] [24] [26] use non-inflammable atmospheres.
Because none of the test rigs available in the literature meet these requirements, a completely new test rig was designed; the methodology is outlined in the following section.

3 Methodology

This section introduces the newly developed, innovative test rig system that meets the requirements for investigating spark discharge from the previous section. It also presents the measuring techniques as well as the methodology for evaluating the measurement data.

3.1 Arc Test Rig Setup

Figure 2 shows a CAD mock-up of the test rig and its key components. The rig consists of a closed-loop flow circuit that is filled with the desired medium and pressurized to the target pressure through a filling valve. A blower, which consists of a radial compressor with a hermetically sealed casing, a magnetic coupling and an electric motor allows the setting of the required flow velocity at the spark plug. A heat exchanger maintains a constant gas temperature in the system. A mass flow meter based on the Coriolis principle is located downstream of the heat exchanger and measures the mass flow in the piping circuit; in this manner, the flow velocity at the spark plug is derived.

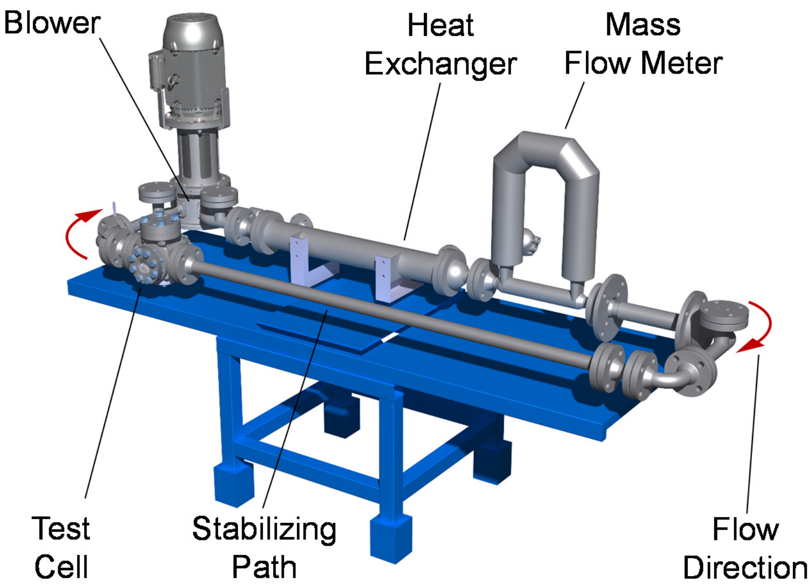

Figure 2: CAD mock-up of the arc test rig

The centerpiece of the test rig is the test cell with optical access, upstream of which is a stabilizing path that provides a hydrodynamic entrance length so that a defined and fully developed flow pattern is set before the medium reaches the spark plug in the test cell. A turbulence grid may be inserted to influence the turbulence of the flow at the spark plug. The test cell has three large optical accesses through which spark discharge can be recorded with a high-speed camera from different angles. Downstream of the test cell is an outlet section that is long enough that flow from the spark plug is not negatively influenced by any flow deflection in the bends. Before the flowing medium enters the radial compressor, a filter protects the turbomachine from damage due to debris transported by the gas.

This setup allows the boundary conditions in the system to be varied over a wide range according to the requirements described in section 2. Table 1 provides an overview of the targeted ranges for the basic operating parameters pressure, temperature and flow velocity at the spark plug. The test rig was specially designed to obtain the values in Table 1 with an atmosphere of air, nitrogen or carbon dioxide.

Table 1: Technical data of the arc test rig [13]

Parameter	Minimum Value	Maximum Value
Pressure	1 bar	60 bar (at 80 °C) 100 bar (at 20 °C)
Temperature	20 °C	80 °C
Velocity	0 m/s	30 m/s

The integration of the optical accesses in the area of the spark plug is particularly challenging in the design of the test cell; these accesses must not disturb the defined flow pattern at the spark plug. At the same time, the test cell must be able to withstand the conditions in Table 1. The solution was provided by the double-walled design shown in Figure 3. A thin-walled inner pipe with a square cross-section facilitates the desired flow geometry while a solid outer pipe safeguards the pressure resistance of the system. The flow passes from the stabilization path through the test cell and to the outlet section completely via the inner pipe, which is sealed off from the outer pipe. A small hole in the stabilization path guarantees pressure compensation between the inner and outer pipes.

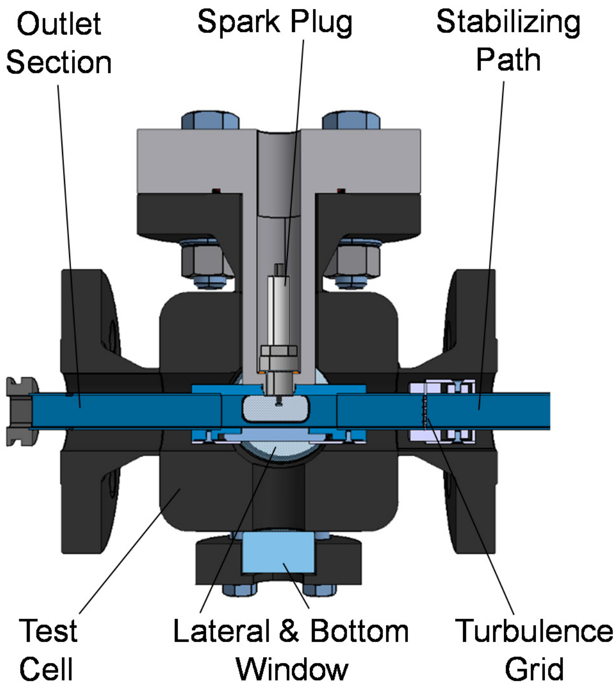

Figure 3: Double-walled design and optical access of the test cell

A hydrodynamic entrance length (stabilizing path) more than eighty times the hydraulic diameter [32] upstream of the test cell yields a fully developed turbulent pipe flow is achieved at the spark plug. To influence the turbulence level in the flow at the spark plug, an optional turbulence grid can be inserted into a slot in the inner pipe upstream of the spark plug.

The electric arc behavior is captured with a high-speed camera from three different angles through two optical accesses parallel to the spark plug axis and the flow direction and one access orthogonal to the spark plug axis. The borosilicate glasses are flush with the inner surface of the rectangular pipe so that flow is not disturbed by the optical access. Spark plugs with a thread diameter of up to 18 mm can be used and the orientation of the spark plug to the flow direction is adjustable. Prior to the measurements, the spark plug was replaced by a constant temperature anemometry probe that recorded the flow velocity at the spark plug electrode as a function of mass flow, pressure, temperature and atmosphere. Knowledge of this relationship is required to set the desired flow velocity at the spark plug without having to measure it directly during the arc behavior investigations.
To sum up, the test rig has several important features that distinguish it from previous setups for investigating spark behavior.

- Option to investigate spark behavior with a high flow velocity (up to 30 m/s), high pressure (up to 60 bar) and temperatures of 20 – 80 °C at the spark plug
- Defined flow condition at the spark plug obtained with a stabilizing path that ensures fully developed turbulent flow in the pipe
- Option to vary turbulence at the spark plug by inserting a turbulence grid upstream of the spark plug
- Option to view the spark plug through optical accesses on three sides simultaneously
- Measurement of flow velocity at the position of the spark plug with a constant temperature anemometry system

3.2 Measuring Instruments

Standard measuring instruments and optical measuring instruments are used to record all relevant measurands on the test rig. Standard measuring instruments are further divided into slow measuring instruments, with sampling rates up to 50 samples per second (S/s), and fast measuring instruments, with sampling rates up to 10 megasamples per second (MS/s).

Slow measurands include pressure, temperature and mass flow. Fast measurands include primary current, secondary current and voltage in the ignition system as well as the flow velocity at the spark plug. The flow velocity is measured with a highly accurate constant temperature anemometry system. As described above, the probe of this system replaces the spark plug. The recorded data revealed a correlation between the local flow velocity and mass flow, pressure, temperature and atmosphere.

A Fastcam SA-X2 high-speed camera from Photron, inc. that has a lens with a focal length of 100 mm recorded the processes in the test cell. The camera has a maximum frame rate of 600,000 frames per second at a spatial resolution of 128 x 24 pixels.

3.3 Post-processing

One direct consequence that the flow field has on the arc at the spark plug is spark stretching, i.e. the increase in the overall arc length due to flow motion. As a result, arc length is considered to be an indicator for the influence of flow velocity. To quantify the arc length, LEC GmbH developed an algorithm that automatically extracts numerical values from the high-speed images.

The arc length is computed starting with the raw image, which is transformed into a binary black and white image, cf. Figure 4a) and b). The algorithm starts with a high threshold value of 90%. After binarization, the algorithm checks whether any disjunct areas appear in the white region as a result of binarization. The threshold value is iteratively reduced until a simply connected region is obtained, cf. Figure 4c). In the following step, the interior is removed so that only the outer contour remains of the formerly white region of the binarized image, cf. Figure 4d). The arc length is computed as half the length of the outer contour. In addition, another algorithm verifies the validity of an image by checking whether the arc roots are in close proximity to the electrode surfaces.

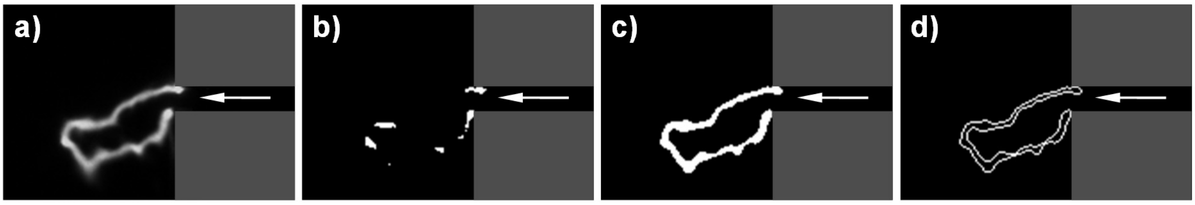

Figure 4: Image processing to determine arc length [4]

It must be emphasized that the value of the arc length is generated from two-dimensional images; the algorithm does not consider arc deflection in the third dimension.

4 Selected Results

Applying the methodology explained above, this section presents sample results that illustrate the possibilities with the arc test rig. The influence of pressure at the spark plug is examined in detail. The measurements were performed with an air atmosphere, a flow velocity of 30 m/s at the spark plug, a spark current duration of 900 µs, a spark current level 50% of the maximum possible current and a system temperature of 25 °C. The J-shaped ground electrode of the spark plug was located opposite the camera, enabling good optical access to the electrode gap and minimal disturbance of the flow pattern at the electrode gap. The ignition system is a MCDI system as described in section 2, which facilitates a comparison between the results from the arc test rig and those from analogous engine test beds.

Figure 5 provides samples of high-speed recordings of arc behavior at different pressures. The time scale and flow advance from right to left. The first row illustrates the results at a system pressure of 35 bar, the second row at 10 bar and the last row at 0 bar (gauge). The time step between each image is constant. Each picture shows the spark plug electrodes and the arc at the specific time step in one single measurement cycle.

It can be seen that as the pressure goes up, arc illumination as well as arc deflection increase. As arc length grows, the folding of the arc increases. The bright flash in the first image with the 10 bar system pressure coincides with arc breakdown, illustrating the initial plasma expansion due to the blast wave that results from the fast energy release during breakdown. At all illustrated pressures and time steps, the arc roots are already located downstream of the electrodes as they move with the flow. In the last three images with a system pressure of 35 bar, the lower arc root is not on the electrode but on the electrode holder (bright rectangular shape in the image). Due to short circuits of the arc column caused by turbulent motion (cf. [33]), a pronounced shortening of the arc length is observed, such as in the last three images at a system pressure of 10 bar. It is assumed that the increasing illumination of the arc as the system pressure increases is related to the rise in dissipation of secondary energy that occurs as the system pressure increases (cf. Figure 6). The greater arc deflection with increasing system pressure is assumed to be due to the reduced influence of inhomogeneous arc heating at higher pressure, cf. [2] [16].

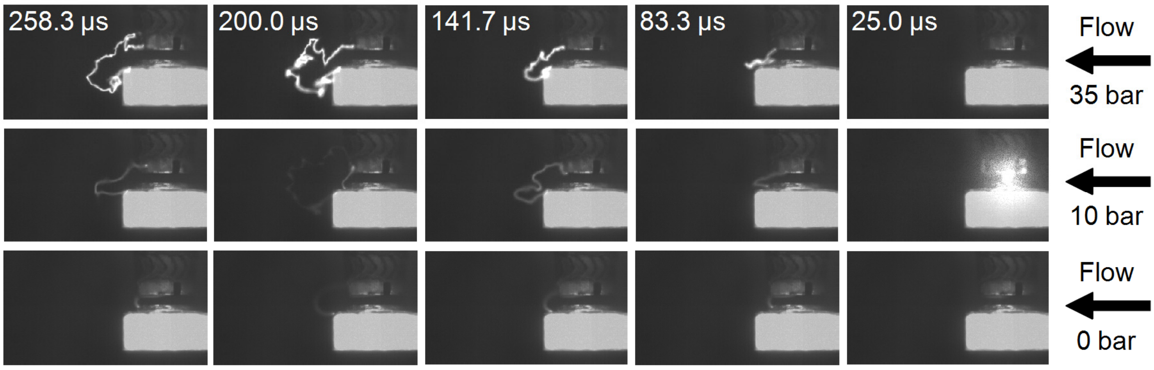

Figure 5: Influence of pressure on electric arc behavior

To better understand arc behavior, the measurement points shown in Figure 5 are analyzed using the image post-processing algorithm. The results are shown in Figure 6. The first diagram of Figure 6 plots the arc length, the second diagram the secondary voltage and the third diagram the dissipated secondary energy over time. Each pressure is indicated by a different color. The thick lines represent the mean curves calculated from 50 consecutive cycles and the thin lines represent single cycles. The more a single cycle differs from the mean curve, the lighter its color. The dashed lines represent one standard deviation.

The qualitative statements from Figure 5 can be evaluated quantitatively based on the analysis of the arc length traces in Figure 6. The results confirm that the arc stretches more when the pressure is increased as indicated by its greater arc length. At all pressures, a certain level of arc length is not exceeded, which is a result of arc shortening effects during the arc burning phase.

As the pressure increases, the absolute value of the arc breakdown voltage (first distinct minimum in the secondary voltage curve) also increases and is reached at a later time. This effect is also visible in the first images at 25 µs in Figure 5; at 0 bar, the arc is already burning (yet is hardly visible due to the low illumination). At 10 bar, the arc breakdown is just starting to occur and at 35 bar, the breakdown voltage has not yet been reached.

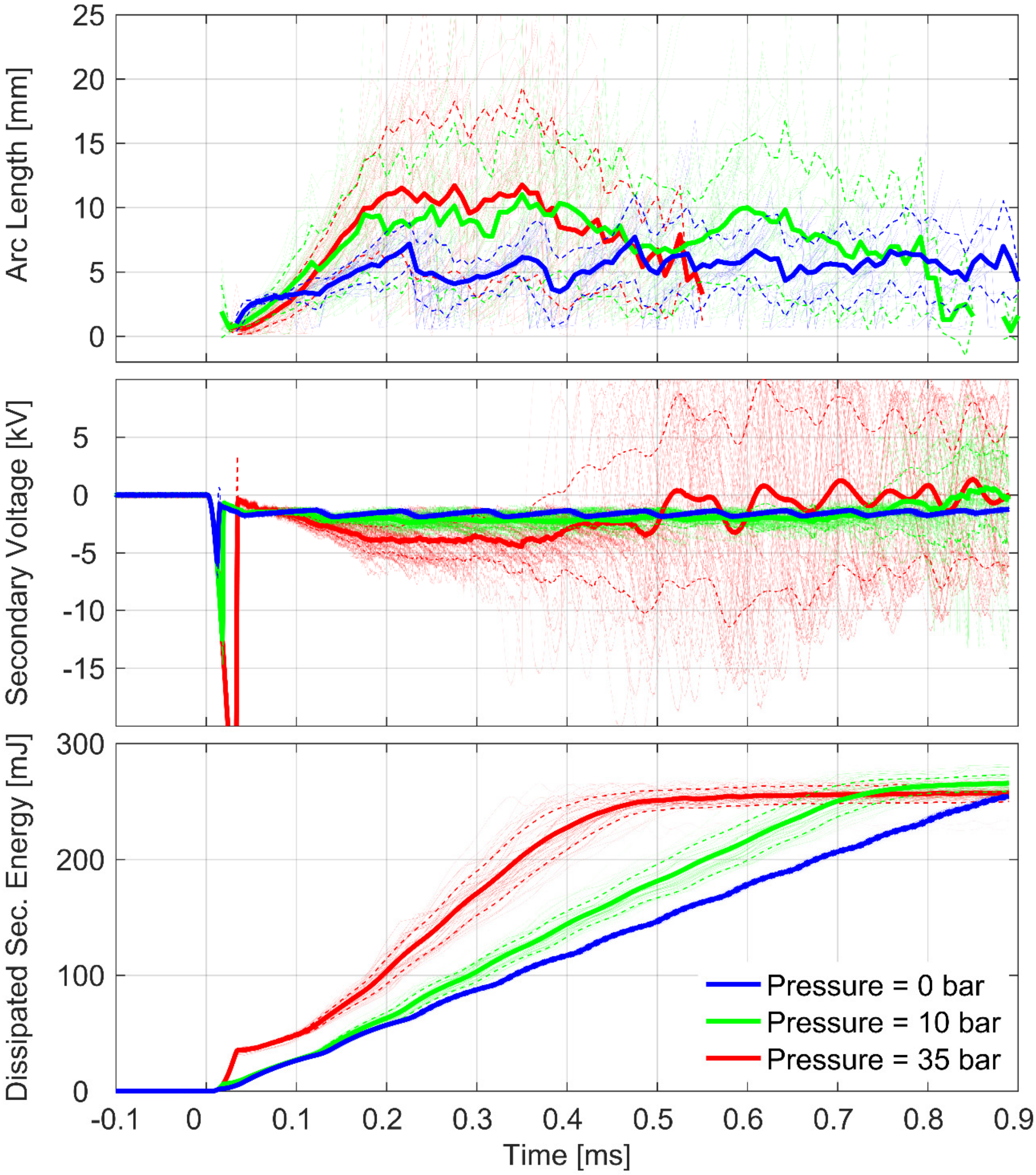

Figure 6: Influence of pressure on arc length, secondary voltage and dissipated secondary energy

In addition, it is evident that despite the controlled boundary conditions upstream of the spark plug (steady-state mean flow velocity and a defined flow profile), the cycle-to-cycle variation in arc length increases at high pressures. While the secondary current from the ignition system is controlled so it remains as constant as possible during the entire spark duration, the secondary voltage history and its cycle-to-cycle variation are strongly influenced by arc length. This is reflected in the cycle-to-cycle variation in the dissipated secondary energy that directly causes cycle-to-cycle variations in the spark energy input to the flowing gas, cf. Figure 6. As the arc length increases, the secondary voltage goes up, leading to a steeper rise in the total spark energy that is introduced. Even though the spark current duration is set to a constant target value of 900 µs, the arc burning time at 35 bar is significantly shorter because the energy limit of the ignition system has been reached, which is indicated by a plateau in the dissipated secondary energy.

These measurement results have resulted in a deeper understanding of the influence of system pressure on electric arc behavior. The measurement data can also be used to improve and validate the electric arc model currently under development at LEC GmbH.

5 Summary and Outlook

This paper presented a test rig on which electric arc behavior can be investigated under engine-like flow conditions at the spark plug in non-combustible atmospheres in order to better understand and optimize the ignition process in internal combustion engines. The setup allows investigations of the influences of the ignition system, the flow conditions and the electric arc behavior on each other and provides a large database for validating arc models. The requirements for the test rig were derived from a description of the fundamentals of electric gas discharge. The geometric design for excellent optical access, defined flow and flexible spark plug installations was determined and the variation ranges for important parameters were defined: flow velocities at the spark plug electrodes (0 – 30 m/s), pressure (1 – 60 bar) and temperature (25 – 80 °C).

A methodology for consistent experimental investigations of electric arc behavior on an arc test rig was elaborated and presented. The setup of an innovative test rig as well as the corresponding measurement techniques and the post-processing methodology were explained in detail. The test rig was set up as a closed circuit for non-inflammable gases that consists of a blower and an optically accessible test cell connected to a stabilizing path located upstream that allows a defined and fully developed flow. A wide variety of standard measuring instruments for pressure, temperature, mass flow, current and voltage were applied along with optical measuring techniques that use a high-speed camera. Image processing algorithms were developed to generate quantitative values from qualitative measurements and thus facilitate the interpretation of the results.

Based on the sample results obtained by varying system pressure at the spark plug, the methodology was applied in spark investigations and conclusions regarding electric arc behavior were presented. The key findings are that the stretching of the electric arc increases as the system pressure increases; this is apparent from the greater arc length. The cycle-to-cycle variation in arc length also increases as pressure increases. The arc length in turn influences the secondary voltage and its cycle-to-cycle variation. Consequently, the spark energy input to the flowing gas also depends on the cycle-to-cycle variation.

To make further progress in the two main areas of emphasis of the research presented in this paper, i.e. a better understanding of the ignition process in large spark ignited gas engines and improved and validated ignition and combustion simulation models, the methodology described above will be applied in future research. Potential topics include evaluations of various spark plug geometries in combination with different turbulence levels at the spark plug and the testing of different ignition systems and ignition parameter setups.

6 Acknowledgement

The authors would like to acknowledge the financial support of the "COMET - Competence Centres for Excellent Technologies Programme" of the Austrian Federal Ministry for Transport, Innovation and Technology (BMVIT), the Austrian Federal Ministry of Science, Research and Economy (BMWFW) and the Provinces of Styria, Tyrol and Vienna for the K1-Centre LEC EvoLET. The COMET Programme is managed by the Austrian Research Promotion Agency (FFG). The authors would further like to thank GE Jenbacher GmbH & Co OG and Mr. Arno Gschirr from Hoerbiger Ventilwerke GmbH & Co. KG for their support and for providing equipment during the tests.

Literature

[1] Warnecke, W.; Karanikas, J.; Levell, B.; Mesters, C.; Schreckenberg, J.; Adolf, J.: "Gas – A Bridging Technology for Future Mobility?", contribution at: "34th International Vienna Motor Symposium", Vienna, 2013.

[2] Meyer, G.; Gschirr, A.; Lindner-Silwester, T.; Stadlbauer, K.: "Recent Advances in Modeling Modulated Capacitive High- Energy Ignition Systems and Application of the Findings in a New Generation of Ignition Systems," in: Eichlseder, H. (Ed.): "14th Symposium The Working Process of the Internal Combustion Engine," Graz, 2013.

[3] Wimmer, A.; Pirker, G.; Engelmayer, M.; Schnessl, E.: "Gas Engine Versus Diesel Engine: A Comparison of Efficiency", in: "MTZ Industrial" Volume 1, November 2011, pp. 2-6.

[4] Pirker, G; Wimmer, A.; Meyer, G.; Kiesling, C; Nickl, A; Tilz, A: "Diagnostic Methods for Investigating the Ignition Process in Large Gas Engines" in "Proceedings of 13th International AVL Symposium on Propulsion Diagnostics", Baden Baden, June 2018, p.5f.

[5] Poggiani, C.; Battistoni, M.; Grimaldi, C. N.; Magherini, A.: "Experimental Characterization of a Multiple Spark Ignition System," in: "Energy Procedia," Volume 82, December 2015, pp. 89–95.

[6] Brüggeman, D.; Hüttl, C.: "Stand der Entwicklung bei der Laserzündung", in: "Motortechnische Zeitschrift", in "MTZ - Motortechnische Zeitschrift", Volume 70, 2009, Issue 3, pp. 228-231.

[7] Herdin, G.; Klausner, J.; Weinrotter, M.; Graf, J.; Wimmer, A.: "GE Jenbacher's Update on Laser Ignited Engines" in: "Proceedings of ICEF 2006, Fall Technical Conference of the ASME Internal Combustion Engine Division", 2006.

[8] Burrows, J.; Lykowski, J.; Mixell, K.: “Corona Ignition System for Highly Efficient Gasoline Engines”, in: “Motortechnische Zeitschrift, MTZ worldwide Edition” Volume 74, 2013, Issue 6, pp. 38-41.

[9] Rixecker, G.; Bohne S.; Adolf, M; Becker, M; Trump, M; Bargende, M.: “The High Frequency Ignition System Eco Flash”, in: Kratzsch, M.; Günther, M. (Eds.): “1st International Conference: Advanced Ignition Systems for Gasoline Engines”, Renningen, 2012.

[10] Lepley, J .; Brooks, K.; Bell, D.: “A New Technology Electronic Ignition Which Eliminates the Limitations of Traditional Ignition Systems,” Paper No. 173, CIMAC Congress 2010, Bergen.

[11] Franke, A.; Reinmann, R.: “Calorimetric Characterization of Commercial Ignition Systems”, SAE technical paper 2000-01-0548, 2000.

[12] Maly R.; Herweg R.: “Spark Ignition and Combustion in Four-Stroke Gasoline Engines”, in: Arcoumanis, C.; Kamimoto, T. (Eds.): “Flow and Combustion in Reciprocating Engines”, Berlin, Heidelberg, 2009, pp. 1-67.

[13] Tilz, A.; Meyer, G.; Kiesling, C.; Pirker, G.; Salbrechter, S.; Wimmer, A.: “Design of a Test Rig of Fundamental Investigations of Spark Characteristics”, in: “International Journal of Engine Research”, submitted 2018.

[14] Edels, H.: “Properties and theory of the electric arc. A review of progress”, in: “Proceedings of the IEE - Part A: Power Engineering”, Volume 108, 1961, Issue 37, 1961, pp. 55-69.

[15] Liu, K.; Burluka, A. A.; Sheppard, C. G. W.: “Turbulent flame and mass burning rate in a spark ignition engine”, in: “Fuel” Volume 107, 2013, pp. 202-208.

[16] Meyer G.; Salbrechter S.; Tilz A.; Wimmer A.: “Assessment of Electric ARC Models Used in Recent Spark Ignition Models” in: “Digital Proceedings of the 8th European Combustion Meeting”, Dubrovnik, 2017, pp. 644–648.

[17] Meyer, G.; Stadlbauer, K.; Gschirr, A.; Lindner-Silwester, T.; Puttinger, S.: “Modeling of Modulated Capacity Discharge Ignition Systems”, in: “Proceedings of the 8th Dessau Gas Engine Conference”, Dessau Roßlau, 2013.

[18] Ast, G.: “Vergleich Laserzündung mit Zündkerzenzündung”, Diploma thesis, Vienna University of Technology, 2004.

[19] Ko, Y.; Anderson, R. W.; Arpaci V. S.: “Spark Ignition of Propane-Air Mixtures Near the Minimum Ignition Energy: Part I. An Experimental Study”, in: “Combustion and Flame”, Volume 83, 1991, Issue 1-2, pp: 75-87.

[20] Lim, M.; Anderson, R.; Arpaci, V.: “Prediction of Spark Kernel Development in Constant Volume Combustion”, in: “Combustion and Flame”, Volume 69, 1987, Issue 3, pp. 303-316.

[21] Herweg, R.; Maly, R.: “A Fundamental Model for Flame Kernel Formation in S. I. Engines”, SAE technical paper 922243, 1992.

[22] Herweg, R.; Begleris, P; Zettlitz, A.; Ziegler, G. F. W.: “Flow Field Effects on Flame Kernel Formation in a Spark-Ignition Engine”, SAE technical paper 881639, 1988.

[23] Sayama S.; Kinoshita M.; Mandokoro Y.; Fuyuto T.: “Spark ignition and early flame development of lean mixtures under high-velocity flow conditions: An experimental study”, in: “International Journal of Engine Research”, 2017.

[24] Schneider, A.; Leick, P.; Hettinger, A.; Rottengruber H.: “Experimental studies on spark stability in an optical combustion vessel under flowing conditions”, in: Liebl, J.; Beidl, C. (Eds.): “Internationaler Motorenkongress 2016, Mit Konferenz NFZ-Motorenentwicklung, Proceedings”, 1st edition, Wiesbaden, 2016, pp. 327-348.

[25] Gardiner, D. P.; Wang, G.; Bardon, M. F.; LaViolette, M.; Allan W. D.: “An Experimental Study of Spark Anemometry for In-Cylinder Velocity Measurements”, in: “Journal of Engineering for Gas Turbines and Power”, Volume 130, Issue 4, 2008.

[26] Verhoeven, D.: “Spark Heat Transfer Measurements in Flowing Gases”, contribution at: “SAE Fuels and Lubricants Meeting and Exposition”, Toronto, 1995.

[27] Yu, S.; Xie, K.; Han, X.; Jeftic, M.; Gao, T.; Zheng, M.: “A Preliminary Study of the Spark Characteristics for Unconventional Cylinder Charge with Strong Air Movement”, in: “Proceedings of the ASME 2011, Internal Combustion Engine Division Fall Technical Conference, ICEF”, West Virginia, 2011.

[28] Pashley, N.; Stone, R.; Roberts, G.: “Ignition System Measurement Techniques and Correlations for Breakdown and Arc Voltages and Currents”, SAE 2000 World Congress, technical paper 2000-01-0245, Detroit, 2000.

[29] Universitat Politècnica de València, CMT-Motores Termicos: “Flow test rigs: Hot and high flow rig”, online: http://www.cmt.upv.es/EF02_03.aspx, accessed on: 2017-02-01.

[30] Günther, M.: “Ignition Sparks in Slow Motion”, in: “auto motion, IAV's Customer Magazine”, Issue 01/2015, Berlin, pp. 30-32.

[31] Günther, M.; Nicklitzsch, S.; Tröger, R.; Adolf, M.: “Optimizing the Spark Position While Allowing for the Effect of In Cylinder Flow”, contribution at: “IAV International Conference on Ignition Systems for Gasoline Engines 2012”, Berlin, 2012.

[32] Zanoun, E. S.; Kito, M.; Egbers, C.: “A Study on Flow Transition and Development in Circular and Rectangular Ducts”, in: “Journal of Fluids Engineering”, Volume 131, 2009.

[33] Sayama S.; Kinoshita M.; Mandokoro Y.; Fuyuto T.: “Spark ignition and early flame development of lean mixtures under high-velocity flow conditions: An experimental study”, in: “International Journal of Engine Research”, 2018.