Advanced Plasma and Variable Spark Ignition System

P.P. Krüger[1], B. Visser [1], J. Mackenzie[2]

1: North-West University, Potchefstroom, South Africa
2: Ambixtra (Pty) Ltd., Bryanston, South Africa

Abstract: The performance of spark ignition systems is limited by their small spark gap size and corona ignition systems are costly due to their complexity regarding the prevention of arcing. The Advanced Plasma Ignition (API) system is a hybrid corona and spark ignition system that combines the good performance of corona systems with the low cost of spark systems to achieve a good cost-benefit ratio. First API is presented in comparison to spark and corona systems and then some initial test results are presented.

Keywords: Corona Ignition

1. Introduction

Due to stringent exhaust and fuel consumption requirements, there is currently a surge in innovative ignition systems to address the challenges of modified combustion systems and to extend the diluted operation of existing systems.

Different options exist to improve the efficiency of the gasoline engine, such as charge dilution (by increasing exhaust gas recycling or using leaner mixtures), higher turbulence, incomplete charge homogeneity, variable compression ratios, downsizing and turbocharging. For these technologies it has been found that conventional transistor coil ignition (TCI) systems do not always give effective ignition performance. There has been recurring efforts to introduce alternative ignition systems to address the shortcoming of TCI systems, but the low cost of current TCI systems (resulting in a good cost-benefit ratio) still makes them the most favoured ignition system [1]. In a detailed review of new ignition systems [2], it was shown that the most promising candidates are high-energy TCI and corona ignition systems. The high-energy TCI systems have a low cost, but are only a marginal improvement to conventional TCI systems. On the other hand, corona ignition systems give much better performance, but at a higher cost. This is illustrated in Figure 1.

There have been several studies that show the dramatic ignition improvement possible with corona ignition systems. However, corona systems have been slow to enter the market. This may be due to their complexity and the fact that they are not plug-and-play.

In this paper a new ignition system, called Advanced Plasma Ignition (API) is presented, which is a hybrid spark and corona ignition system. To have a system than can do both is not new, and some corona ignition systems also have an arcing mode [3-4]. It will be shown that API makes use of a very simple, inexpensive drive circuit, resulting in a good cost-benefit ratio. API is also plug-and-play, making it easy to compare to and replace current TCI systems.

The main focus of this paper (Section 2) is to present API by comparing it to a standard TCI and corona system. However, some initial test results will also be presented in Section 3.

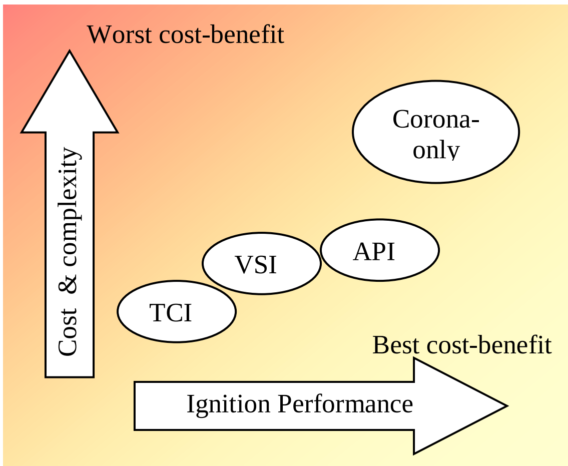

Figure 1: Cost-benefit comparison

2. Comparison of API to TCI and Corona ignition

Before presenting the API system in Section 2.3, a brief overview of a standard spark (Section 2.1) and corona (Section 2.2) ignition system is first given.

2.1 Spark Ignition

<u>Operating Mechanism:</u> A conventional TCI system consists of three elements, a switching device (transistor), a high voltage transformer (coil) and a spark plug as shown in Figure 2 (top). Before the ignition, the transistor is switched on and current starts to flow through the primary winding of the transformer, storing energy in its magnetic field.

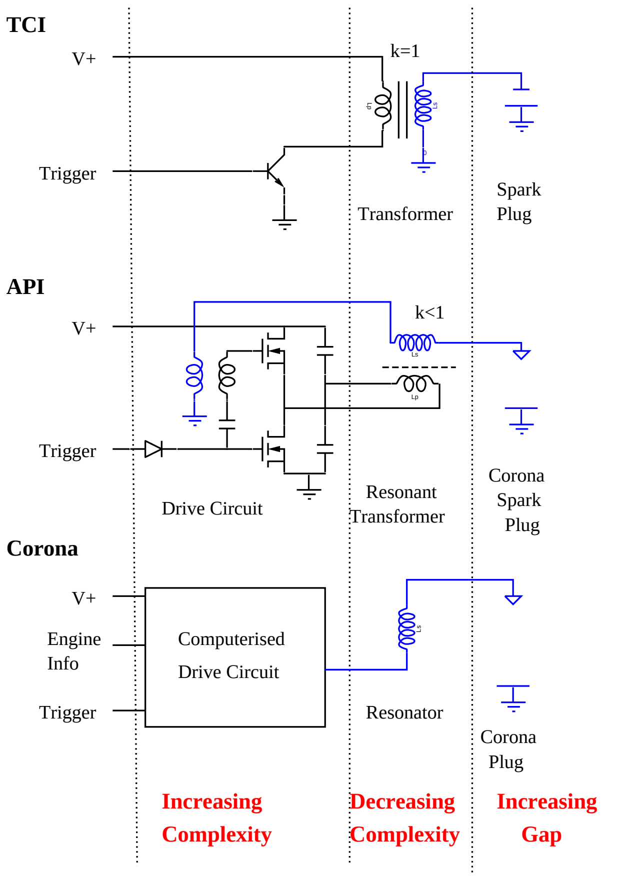

Figure 2: Circuit diagram of TCI, API and Corona Ignition

When ignition is required, the transistor is switched off and the stored magnetic energy is released in two ways. First a high voltage is generated on the spark plug resulting in breakthrough across the spark gap. Then the remaining energy is dissipated in the plasma by means of a decreasing current through the spark.

In order to transfer all the magnetic energy from the transformer's primary to its secondary windings, the windings must share the same magnetic field, i.e. they must have good magnetic coupling (*k* about 1). For this a (iron) magnetic core has to be used.

<u>Drawback:</u> The big drawback of a TCI system is that the spark plug has a small spark gap (see Figure 3 top). Because the spark length is smaller than the typical turbulence length scales, the growth of the initial flame front is slow [5]. The ground electrode also hampers (quenches) the initial flame by being in its way as well as removing heat from it. Note that the ground electrode needs to be thick enough for good heat conduction so that it does not become too hot.

Due to turbulence and inhomogeneities in the air-fuel mixture, the small spark results in a large variance in ignition delay.

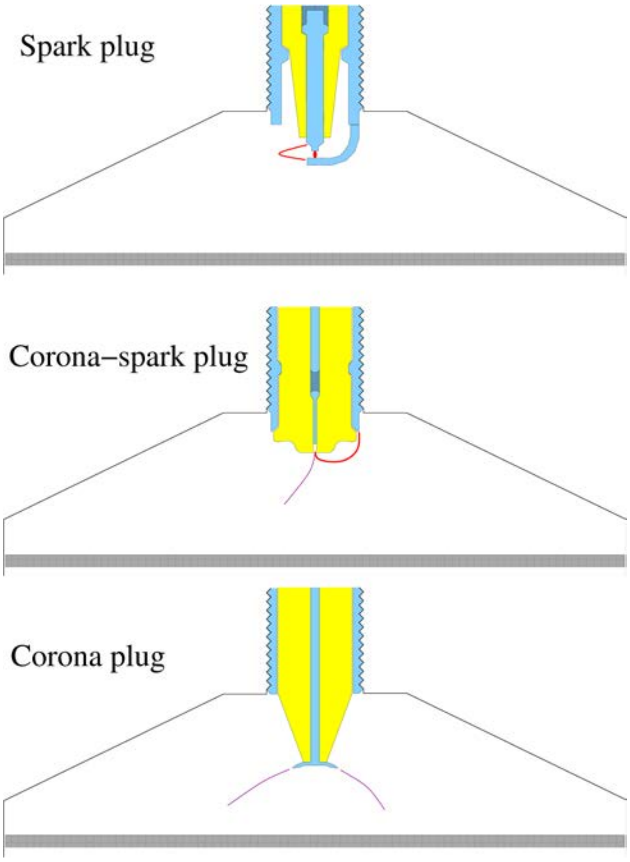

Figure 3: Cross-section of spark and corona plugs inside the combustion chamber

The length of the spark can be increased by designing the combustion chamber to have air flow through the spark gap, resulting in the spark being dragged out of the gap, as shown in Figure 3 and Figure 9. However, too much flow can extinguish the spark by blowing it out, resulting in misfire.

Increasing the energy by increasing the secondary current of a TCI system makes it possible to drag the spark further without it being extinguished. However, higher energy TCI systems leads to faster spark plug wear and due to the inefficiency of the systems, heating of the transformer and spark plug electrodes also becomes a problem.

It is well known that increasing the spark gap size results in better ignition. However, a larger gap requires a higher voltage for breakthrough and the maximum voltage is limited by the dielectric strength of the spark plug ceramic. This becomes problematic for down-sized engines where the cross-section diameter of the spark plug is small.

2.2. Corona Ignition

Operating Mechanism: Corona ignition systems also consist of three parts: a drive circuit, a high voltage resonator and a corona plug as shown in Figure 2 (bottom).

The high voltage resonator and corona plug together have a natural resonance frequency, normally in the order of a few MHz.

When driven at its resonance frequency, the output voltage increases as more energy is fed into the resonator at each cycle, as shown on the left in Figure 4. The voltage increases until the energy loss in the system and corona equals the energy supplied during each cycle, as shown in the middle of Figure 4. Typically, a voltage higher than 30 kV is required at high pressures to generate a corona. In order to generate such a voltage, a drive voltage of about 1 kV is needed (assuming a quality factor of 30).

The corona plug electrode has some sharp tips (see Figure 3 bottom), resulting in a very high electric field at the tip (see Figure 6 middle). The high frequency, high electric field generates a corona discharge from the tip, causing plasma streamers from the tip into the combustion chamber.

In a spark ignition system, energy is used to heat the plasma to a high temperature (as can be seen by the white colour of the arc) and ignition occurs due to the thermal energy of the molecules. However, in a corona ignition system energy is used to excite and ionise the molecules, while the gas stays cold. The volume of the streamers is also much larger than that of a conventional spark, resulting in ignition occurring at several points and turbulent flame front propagation taking place almost from the beginning [5].

Drawback: However, the big challenge with corona systems is to prevent arcing. The plasma streamers grow towards any grounded metal and once it reaches the metal, an arc is formed. In a corona system the duration and intensity of an arc is typically not enough to provide reliable ignition [3]. Arcing will result in wear of the sharp electrode tips and can also cause other components inside the chamber to wear. Frequent arcing will therefore make the sharp tips blunt, resulting in a lower electric field and making it even more difficult to generate a corona without arcing.

To prevent arcing, the electrode tips must be as far as possible from any metal, making the chamber geometry important. Arcing becomes especially problematic in down-sized engines [4] as the distance between the electrode tips and surrounding metal becomes small.

Furthermore, to prevent arcing, the voltage supplied to the corona plug must be varied according to the gas density inside the cylinder. At high gas densities, a high voltage is needed for corona onset, but at low density the same voltage will result in arcing, so that the voltage needs to be reduced with gas density. The voltage difference between the onset of corona and arcing becomes small at large gas densities [4]. To control the voltage, either some feedback from the combustion chamber or mapping is required. This makes the control circuit complex.

These two arc prevention methods make corona system complex and prevent them from being plug-and-play.

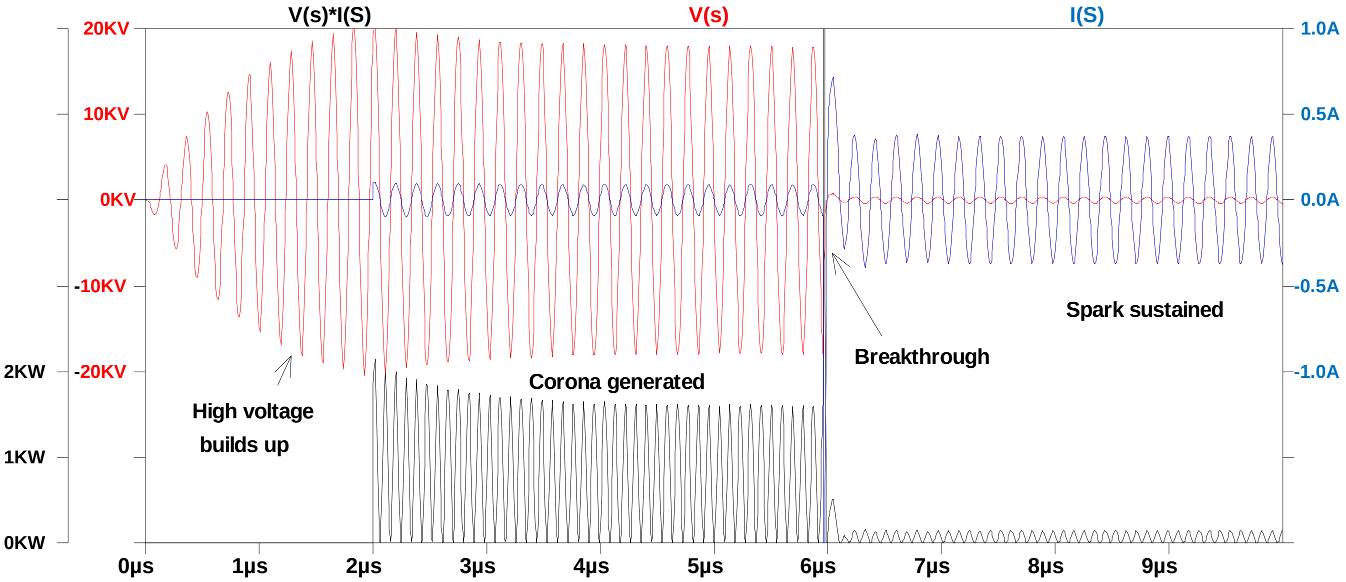

Figure 4: Voltage (red), current (blue) and power (black) waveforms during the three operating modes of API: High voltage build-up mode (left), corona generation mode (middle) and spark sustaining mode (right).

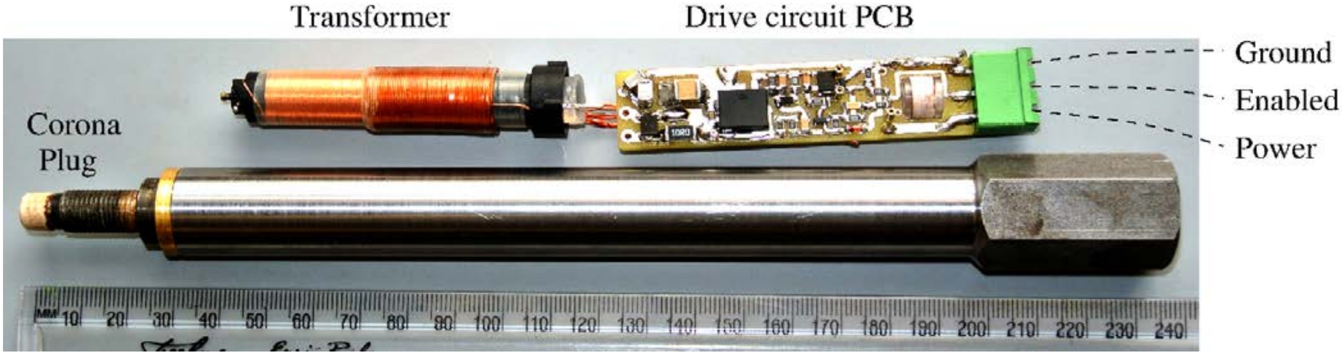

Figure 5: Photo of first API laboratory prototype.

2.3. API: Corona & Spark Ignition

The irony is that in spark ignition systems the electrode gap is small (<1 mm) and if it is increased, too high a voltage is required to generate a spark, but in corona ignition systems the electrode gap is large (>10 mm), but the voltage must be limited to prevent sparking.

API solves these problems by being a hybrid spark and corona ignition system: At high gas densities, a corona is formed as in a corona ignition system and at low gas densities a long spark is formed and sustained as in a spark ignition system.

API also consists of three parts as shown in Figure 2 (middle): A drive circuit, a resonant transformer and a corona-spark plug.

Resonant transformer: API has a transformer like TCI, but unlike TCI the transformer is much smaller with much less windings and with no magnetic material (see for example, Figure 5).

The secondary winding and spark/corona plug have a resonance frequency like a corona system. When the transformer is driven at its resonant frequency, the output voltage is determined by both the winding ratio (like TCI) and the quality factor (like a corona system).

Drive circuit: To drive the transformer at resonance, two transistors in a simple push-pull configuration are used. In order to prevent short-circuit damage and improve reliability, a patented short-circuit protection technique [6] is also used, which is not shown in the figure. The circuit is made to self-oscillate using two feedback mechanisms. First, feedback from the secondary winding is used to make the circuit oscillate at its resonance frequency. When a spark is formed, the secondary side is not resonant any more. A second feedback mechanism (e.g. some inductance between the two transistors' gates) then makes the circuit oscillate at a predetermined frequency. This frequency determines the spark sustain current.

Note that the drive circuit and resonant transformer can easily be used to drive a conventional corona or spark plug.

To demonstrate the efficiency of the drive circuit, it has been used with a conventional spark plug in a system called Variable Spark Ignition (VSI) [7].

Corona-spark plug: The third part of API is the corona-spark plug, shown in Figure 3 (middle). The tip of the HV electrode consists of a thin wire inside the ceramic as shown in Figure 6 (left), forming a small blind bore. Note that a lower voltage is required to start the corona than with a tip in air. Figure 6 shows that the sharp point gives a higher electric field with the ceramic (left) than without the ceramic (middle) for the same voltage. Furthermore, the tip does not become blunt due to wear when it sparks and heat conduction is a much smaller problem than in corona systems (where the electrode is prone to get too hot [2]).

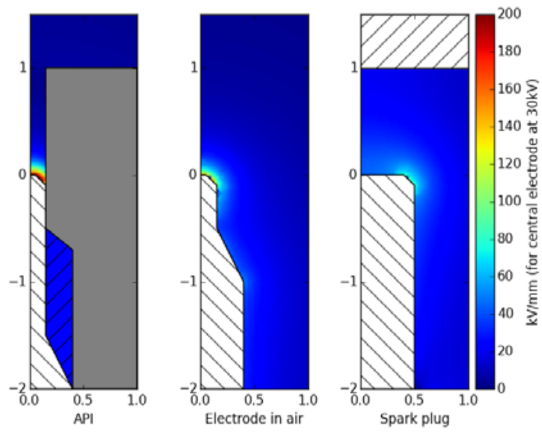

Figure 6: Electrostatic simulation showing the effect of a dielectric material (gray area) on the electric field of a wire at 30 kV. Cylindrical symmetry is assumed.

Similar to a TCI system, API only requires power and an enabling signal. However, no charge time is required. When the enabling signal is applied, a high voltage builds up and a corona is formed like a corona system, shown in Figure 4. A plasma streamer then grows out of the ceramic cavity into the combustion chamber. The cavity also acts as a type of combustion pre-chamber. Even with no fuel in the cavity, the plasma is heated to a high temperature and ejects into the combustion chamber. Figure 7 shows an example of the resulting plasma streamer (see [8] for more detail).

Figure 7: Picture of a corona generated by API

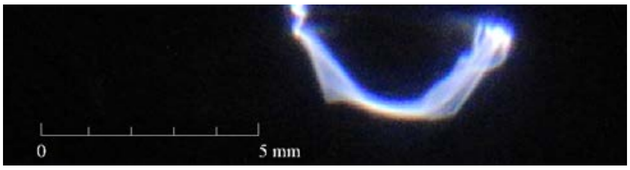

Figure 8: Picture of a spark generated by API

When the gas density is low, the plasma streamer reaches the ground electrode and a spark is formed, as shown in Figure 8. The current supplied by the drive circuit (which can be configured to be up to 1A) then heats the spark (see Figure 4 right) similar to a TCI system. However, unlike a TCI system, the current is kept constant for as long as the enabling signal is applied, which may be several milliseconds. If the spark is extinguished (blown out), the voltage immediately (with a few micro seconds) builds up again to either restrike or form a new corona discharge.

API therefore has two energy transfer mechanisms, one in which energy is supplied to the corona and one in which energy is supplied to the spark, as shown by the black line in Figure 4. The efficiency of the system is mainly determined by the quality factor of the resonant transformer. Even though the resistance of the corona and spark differs several orders of magnitude, an efficiency higher than 50% can be obtained in both modes.

<u>Comparison:</u> Table 1 compares API to TCI and Corona Ignition according to the requirements listed in [1]. Compared to a TCI system, API has a much larger ignition volume. Compared to a corona system, a simpler and cheaper drive circuit is used.

The idea of using a corona to generate a large spark is not new and was already suggested in 1970 [9]. [3] also reports a corona system with an arc mode. However, the drive system is much more complex than that of API.

Note that the component cost of the drive circuit is about $5, which consists mainly of the two power transistors (about $1 each) and of the low-loss capacitors (about $2). The cost of the resonant transformer is expected to be cheaper than a conventional TCI coil as no magnetic material and much less copper is used. The cost of the corona-spark plug is expected to be similar to that of a spark plug. API is therefore expected to be less than $5 more expensive than a conventional TCI system when produced in large quantities.

3. Engine & Laboratory test:

3.1. Corona-spark plug:

The functionality of API has been tested successfully in the laboratory. Figure 5 shows the parts of a first lab prototype where the resonant transformer and drive circuit are located inside a metal tube. Figure 7 and Figure 8 show the resulting corona and spark in pressurised dry air. The corona system operates reliably up to a gas density of 30 kg/cm^3.

Currently prototypes are made available to interested parties for engine testing.

Table 1: Comparison of TCI, VSI, API and Corona Ignition systems

Requirement	TCI	VSI	API	Corona
Secure ignition of highly diluted mixtures	**Bad**	OK	Good	Excellent
Supply of sufficient ignition energy under all operating conditions	**Bad**	OK	Good	Good
Immunity against high flow velocities in the sparking area	**Bad**	Good	Good	Good
Coverage of a big volume to increase ignition probability	**Bad**	**Bad**	Good	Excellent
Low susceptibility to shunting conditions (fouling, wetting)	Good	Excellent	Excellent	Good
Low sensitivity to post assembly position	OK	OK	Good	**Bad**
Ignition at high pressure conditions	OK	OK	Good	OK
Cross-section requirements (Downsizing)	OK	OK	Good	OK
Cost/benefit ratio	Good	Good	Excellent	OK
Reasonable engine control unit ECU applicability	Good	Good	Good	**Bad**
Ignition under critical boundary conditions	**Bad**	OK	Good	Excellent

3.2. VSI: Drive circuit & resonance transformer:

VSI (Variable Spark Ignition) is an ignition system that makes use of the drive circuit and resonant transformer to drive a normal spark plug [7]. Compared to a conventional TCI system it has the advantages that it can sustain the arc for longer periods and with higher currents and that there is always enough energy available to restrike should the spark be blown out. It also has the capability to generate multiple sparks at a rate faster than 100 µs.

To demonstrate its capability to withstand blown out, spark visualisation was done at different flow speeds, as shown in Figure 9. Note that the secondary current is enough to sustain the arc up to flow speeds of 15 m/s. For flow speeds above 15 m/s, the system restrikes each time the spark is blown out, resulting in multiple sparks across the spark gap.

VSI has also been tested on several test engines in both homogeneous and stratified modes.

Figure 10 shows an example of tests done on a 4 cylinder, 1.4l production engine in homogeneous modes. The effect of the VSI system compared to the standard TCI system was investigated at the lean and IGR limits of the engine. The high energy sparks of VSI result in shorter ignition delays (bottom graphs), faster burn rates and a larger misfire free operating range (lower middle graphs). This result in improved stability (upper middle graphs), making stable operation at higher internal exhaust gas recycling (IGR) and leaner operating conditions possible. The engine has about 1 to 2% lower fuel consumption under these operating conditions (top graphs).

Engine tests in stratified mode showed an improvement in combustion robustness and ignition delay for the VSI. This result in stable (misfire free) operation at retarded spark angles which improves fuel consumption.

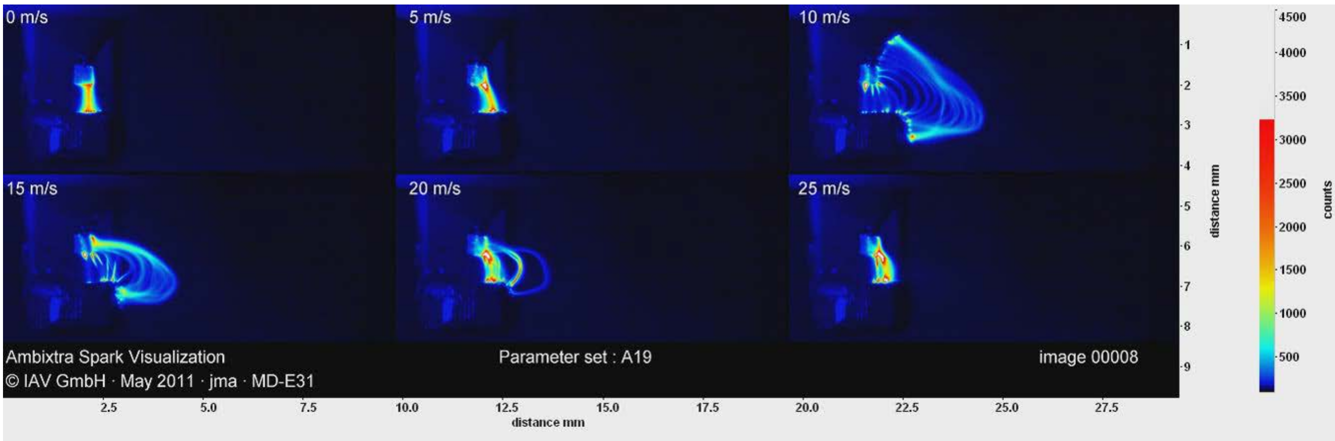

Figure 9: VSI spark visualisation at 1 bar pressure for different gas flow velocities.

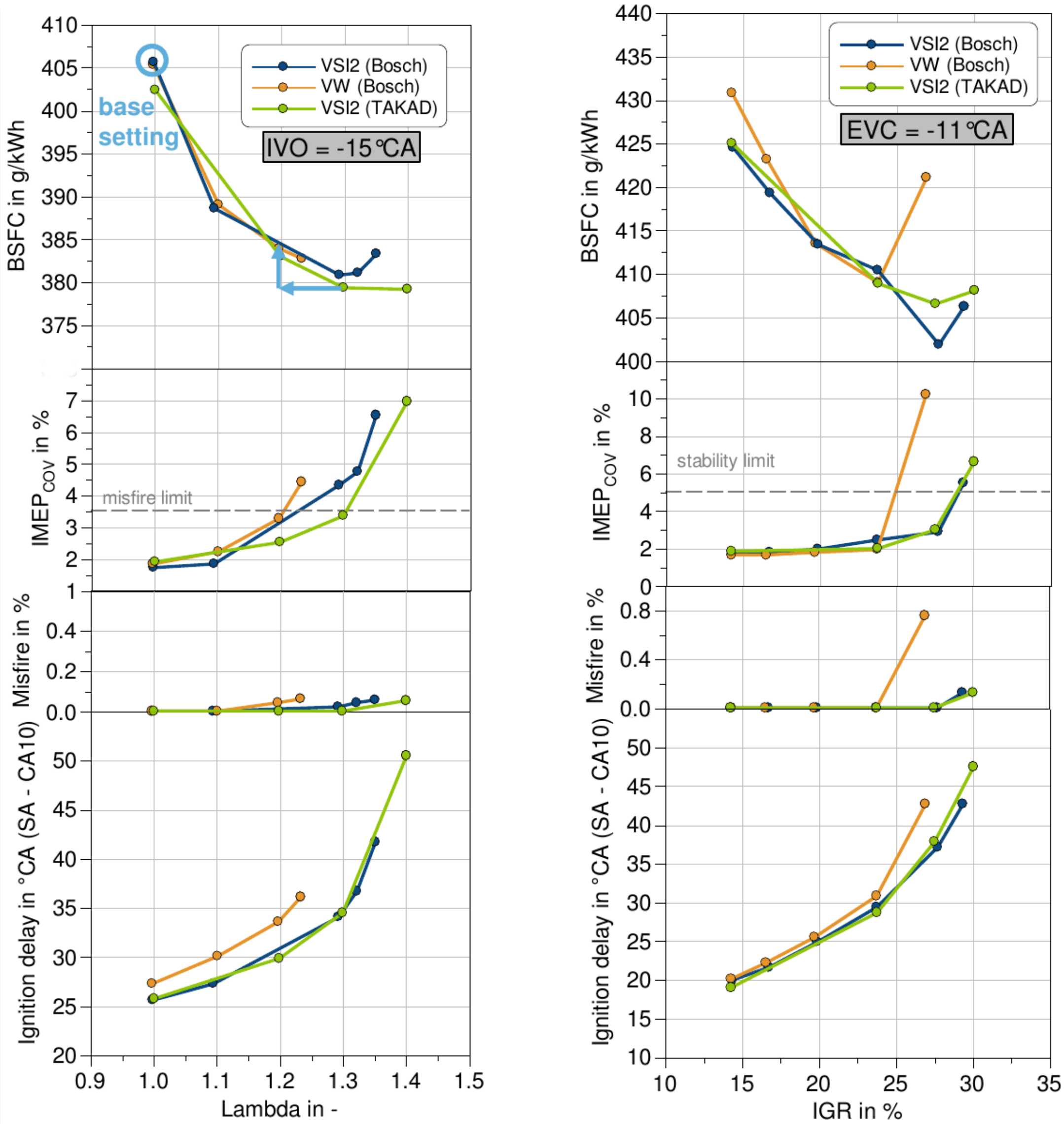

Figure 10: Comparison of VSI with a resistive (blue) and non-resistive (green) spark plug against a standard ignition system (orange) at 2000 rpm/2bar (left) and 1250 rpm/2 bar (right) on a 4-cylinder, 1.4l production engine.

4. Conclusion

The benefit of corona systems is well known compared to conventional TCI systems. However, replacing a TCI system with an optimum corona system is a large step as it requires different combustion chamber optimisations and a complex corona control system.

It is believed that API enables a more gradual switch over, as it is simpler and cheaper than a full corona system and it is also 'plug-and-play' on any standard engine.

VSI is an even smaller step towards a corona system in that it still uses a spark plug to make sparks, but it uses high frequency resonance to efficiently drive the spark plug.

Corona only and spark only ignition system are two extremes in ignition parameter space. Hybrid corona and spark ignition is mostly unexplored. API made it possible to explorer and utilise these hybrid solutions in a cost-efficient manner.

5. Acknowledgement

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6. References

[1] Herweg, R., Karl, G., Haase, D., Dieler, T.: "*Ignition System Requirements for Future Combustion Systems*", 1st International Conference on Advanced Ignition Systems for Gasoline Engines, Berlin, Germany, 2012.

[2] Graf, J., Lauer, T., Geringer, B., Rottengruber, H.: "*Innovative Ignition Systems for Highly Supercharged Downsized Engines*", 1st International Conference on Advanced Ignition Systems for Gasoline Engines, Berlin, Germany, 2012.

[3] Burrows, J.A.: "*Corona Ignition System having selective enhanced arc formation*", US 8,869,766, 2014.

[4] Burrows, J., Mixell, K., Reinicke, P.-B., Riess, M., Sens, M.: "*Corona Ignition – Assessment of Physical Effects by Pressure Chamber, Rapid Compression Machine, and Single Cylinder Engine Testing*" 2nd International Conference on Ignition Systems for Gasoline Engines, Berlin, Germany, 2014.

[5] Wolf, T., Schenk, M., Schroeter, M., Zellinger, F., Klaus, B., Pfeiffer, D., Fischer, H.: "*RF Corona Ignition vs. Spark Ignition: A Comparison for Varying Thermodynamic Conditions and Combustion Strategies of Modern Turbocharged Gasoline Engines*", 2nd International Conference on Ignition Systems for Gasoline Engines, Berlin, Germany, 2014.

[6] Visser, B., Krüger, P.P.: "*A switched mode drive circuit*", PCT patent application PCT/IB2013/ 051501, 2013.

[7] Visser, B., Krüger, P.P.: "*Ignition System*", US patent US8567372 B2, 2013.

[8] Krüger, P.P, Visser, V.: "*Advanced Plasma and Variable Spark Ignition System*", 2nd International Conference on Ignition Systems for Gasoline Engines, Berlin, Germany, 2014.

[9] Terao, K, Yokosuka-shi: *"Wide gap discharge spark plug*", US 3,538,372, 1970.

7. Glossary

API: Advanced Plasma Ignition

VSI: Variable Spark Ignition

TCI: Transistor Coil Ignition

COV: Coefficient of Variance

IMEP: Indicated Mean Effective Pressure

ISFC: Indicated Specific Fuel Consumption

PCB: Printed Circuit Board

HV: High Voltage

IGR: Internal Gas Recycling