High-frequency Ignition System Based on Corona Discharge

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According to the European emission directive, the CO_2 emissions of passenger cars are to drop to a fleet average of 95 g/km from 2020 onwards. Promising approaches to achieving this goal can now be seen in the development of combustion processes for gasoline engines, and a major role is played by dethrottling, which is achieved by lean combustion or by using high exhaust gas recirculation rates. High-frequency ignition is based on the phenomenon of corona discharge and has the potential to be available on time. Under the name EcoFlash, BorgWarner is pressing ahead with its development towards series production.

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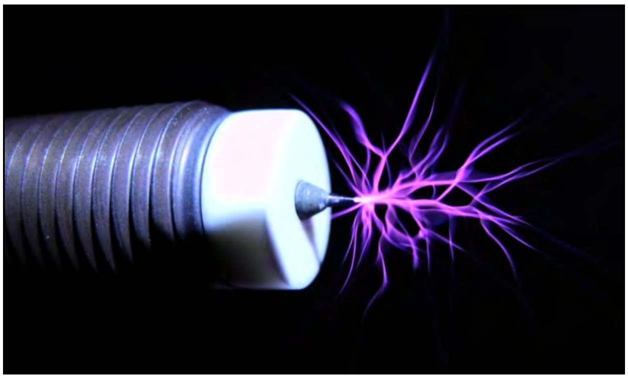
Volume Ignition as an Ideal Solution

The reliable ignition of lean or diluted fuel-air mixtures makes extremely high demands on the ignition system. The energy input of conventional transistor coil ignition systems is generally no longer adequate to limit the increase of the cyclical fluctuations in operating conditions such as these. In addition, the lower burning rates of the diluted mixtures reduce the efficiency benefits which can be achieved. This is the case for homogeneous as well as stratified combustion modes. The latter can at least profit from an extended ignition time, which increases the probability that ignitable mixture is ignited during each combustion cycle.

Meanwhile, all new high-EGR and lean engine concepts currently in the development stage profit to a considerable degree from an enlarged ignition volume, which not only guarantees reliable ignition but can also contribute to a higher burning rate and thus to more efficient energy release by forming spatially distributed flame kernels.

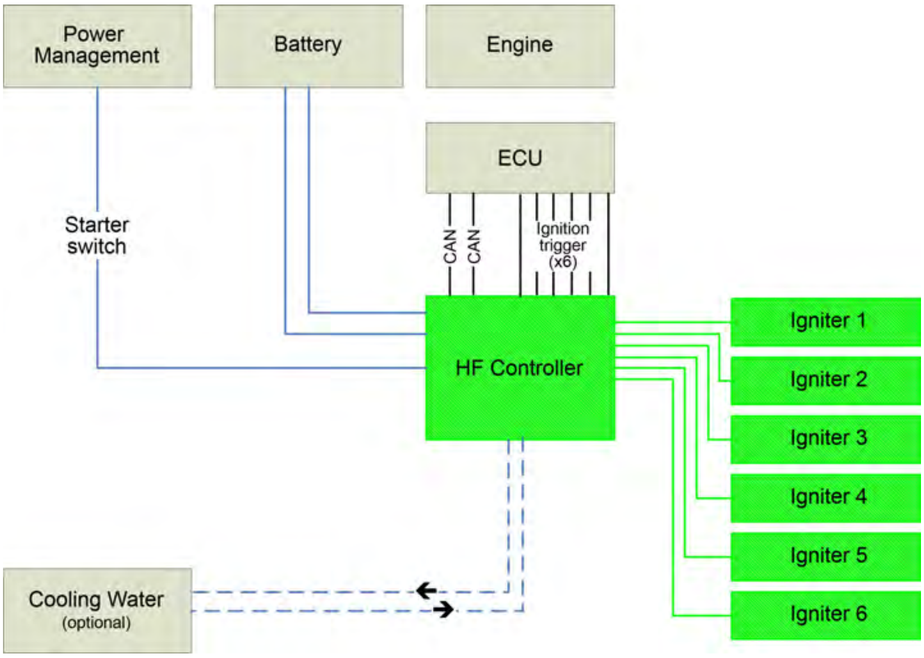
The technology of choice which meets all technical criteria in the field of passenger cars and also has the potential to be available on the market in good time before the CO_2 directive comes into force in 2020 is high-frequency ignition (HFI), which is based on the phenomenon of corona discharge. BorgWarner Emissions Systems is currently pressing ahead with the development of the system named EcoFlash towards series production.

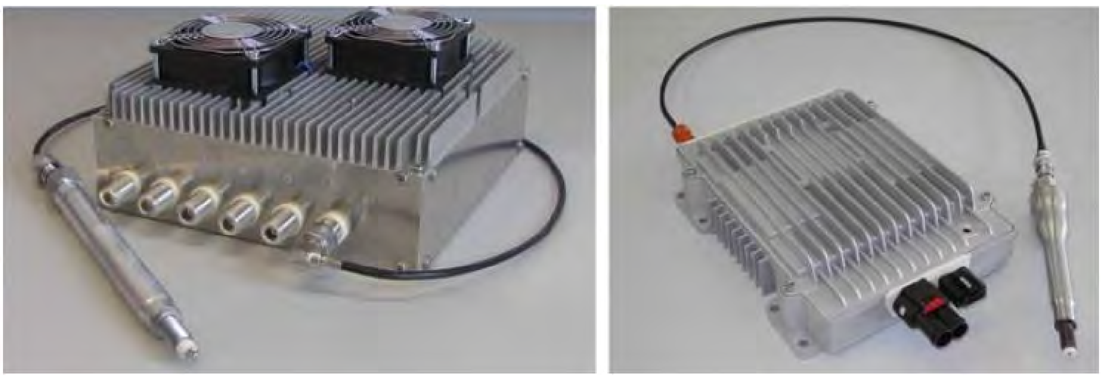


Corona formation on an electrode tip in ambient air

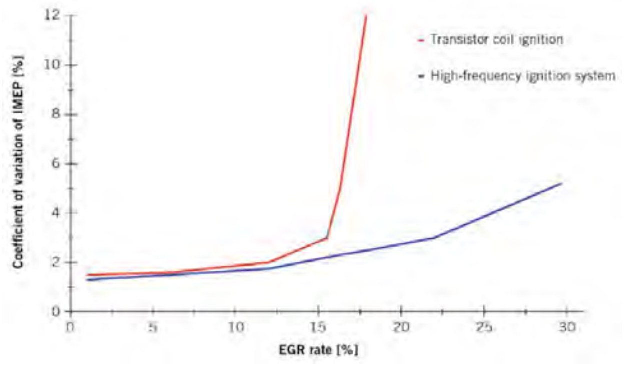
System Layout and State of Development

We refer to [1] for a brief discussion of the corona discharges. What the current concepts for corona ignition systems have in common is that the high voltage required for the gas discharge is generated via resonance transformation using a series resonant circuit [2, 3, 4, 5]. Here it is essential to limit the voltage (depending on the operating point) in such a way that unintentional spark breakthrough cannot occur. This control task is ideally supported by dimensioning the combustion chamber using electric field simulation; this ensures that the field strength above the metal combustion chamber surfaces will never exceed certain threshold values [1]. If corona control is carried out correctly, virtually all of the energy provided for the gas discharge is transferred to the cylinder charge, and in comparison with spark ignition this leads to an advantageous ratio





System layout for the high-frequency ignition (top) and the current A and B prototype systems (bottom)



Running smoothness comparison between a conventional 90 mJ transistor coil ignition (TCI) and the high-frequency ignition system (HFIS) EcoFlash in the case of progressive charge dilution by exhaust gas recirculation (operating point 2000 rpm and IMEP = 6 bar)

between energy input and energy transferred to the process gas.

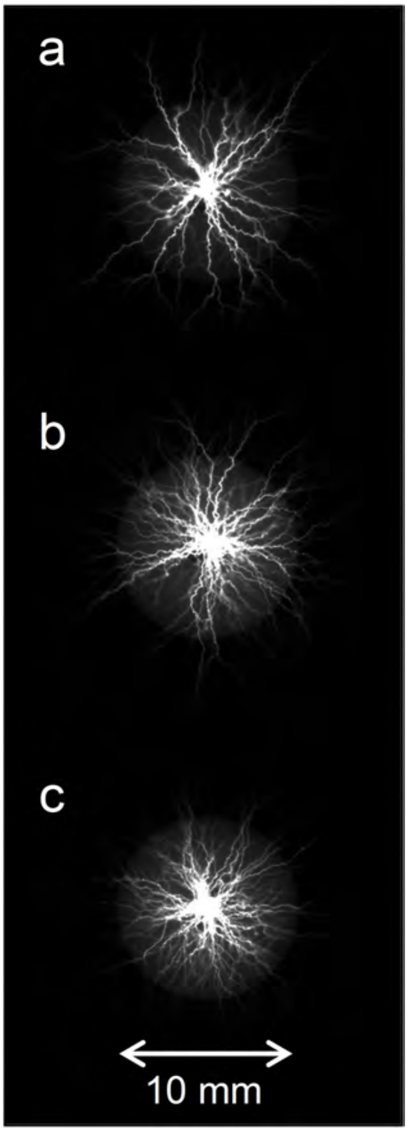
The configuration of the EcoFlash version for use in passenger cars comprises a controller and three to six igniters depending on the number of cylinders. The high-frequency cables between controller and igniters are of the coax type. As the last stage of voltage transformation is carried out by a resonant circuit integrated into the igniters (see above), the voltage to be transferred here is limited to less than 1 kV. The maximum effective power input of the EcoFlash A level prototype system is 350 W in the six-cylinder version. When the A level prototype system was used on a turbocharged 2.0-l four-cylinder engine with intake manifold fuel injection, ignition energies of 50 mJ were adequate in order to comply with a COV_{IMEP} < 2.6 % over a large part of the engine map. Also, an ignition energy of less than 25 mJ was adequate in order to operate, in a further test series, a small two-stroke gasoline engine with a displacement of 92 cm^3 in a speed range between idling and 10,000 rpm [6].

The A level prototype systems which are still largely used in test bench operation and by customers are successively being replaced by B level prototype systems. These are currently undergoing internal validation and include, in addition to an approximately doubled electrical efficiency, a newly developed communication interface.

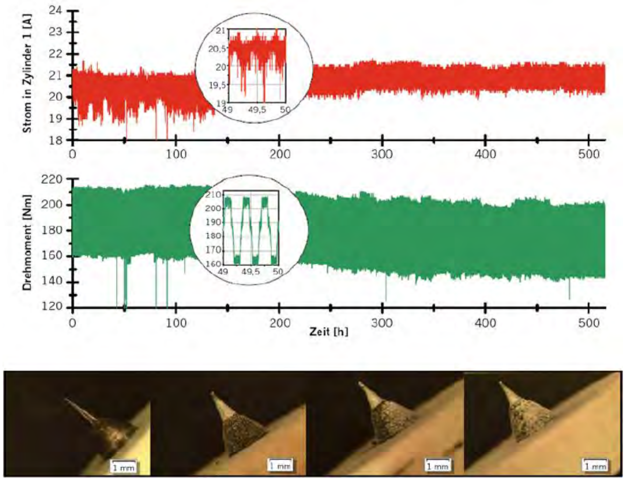
Increasing the EGR Tolerance under Partial Load

A current turbocharged four-cylinder engine with a displacement of 1.4 l and direct injection which was additionally equipped with a cooled low-pressure exhaust gas recirculation system was used for a detailed comparison between the EcoFlash A level prototype ignition system and a conventional transistor coil ignition system with an ignition energy of 90 mJ. The igniter was positioned in the centre of the combustion chamber and the injector was side-mounted. The flat piston bowl designed for combined flow and wall guidance of the mixture did not have to be modified for operation with the high-frequency ignition. However, it is to be assumed that an additional modification of the combustion chamber geometry would have allowed even clearer advantages than those described in the following to be achieved.

The test program included the EGR tolerances under partial load, for load points between 2000 and 4000 rpm and at mean pressure of 2 to 14 bars. Other results concerning the lean limit, the knocking behaviour and the EGR tolerance under full load have already been presented elsewhere [1]. For the example of the load point 2000 rpm/6 bar, EcoFlash shows a considerable increase in the EGR rate in comparison with a transistor ignition. If a running smoothness criterion of COV ≤ 5 % is used, an



Corona formation at high pressures in nitrogen; each individual image shows image sequences integrated over an ignition process with a duration of 500 µs: 20 bars chamber pressure and 80 % DC power setpoint (top), 30 bar and 95 % (middle) and 40 bar and 100 % (bottom)



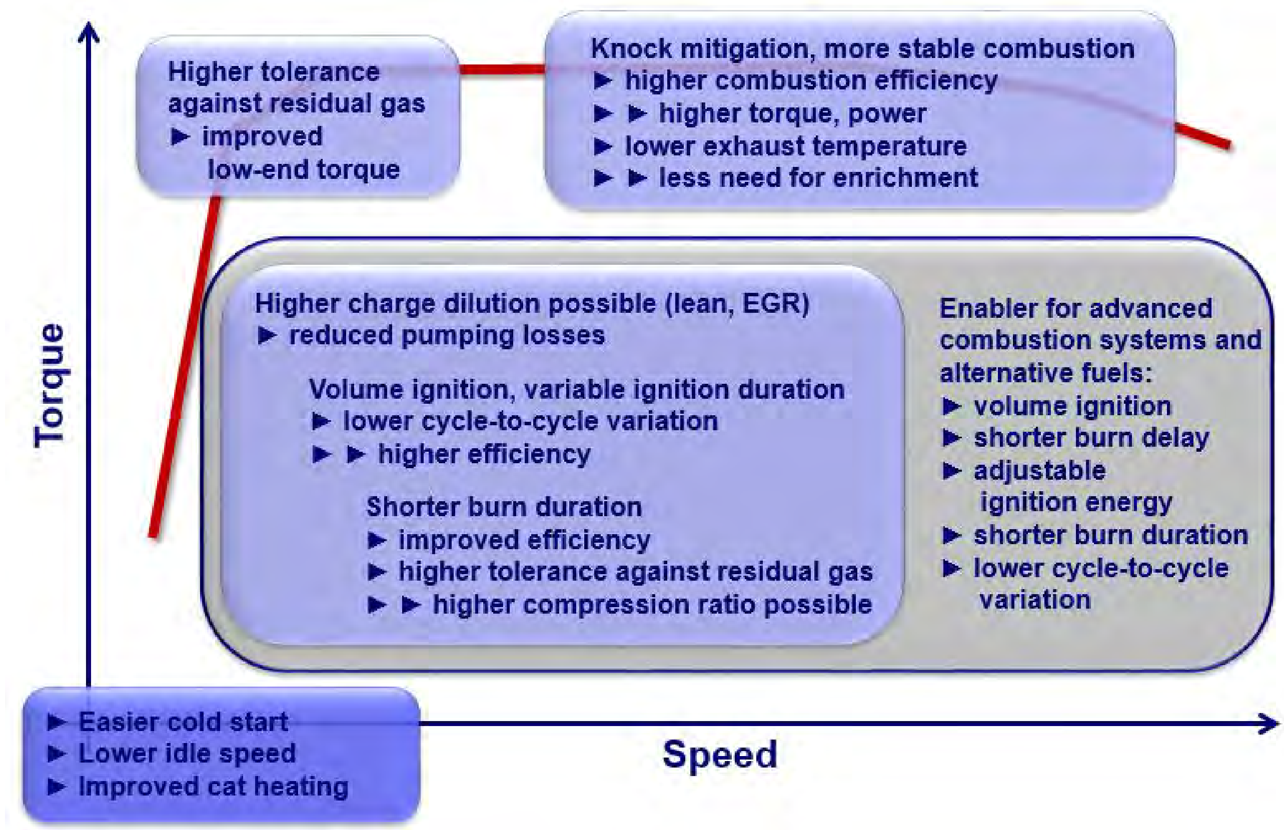
Time behaviour of the primary current during an endurance test under full load with cyclical variation of speed between 2000 and 5500 rpm (top) and electrode wear of an igniter after 0, 150, 320 and 480 h (bottom, all igniters were fully functional at the end of the endurance test)

external EGR rate of 29.7 % is achieved, i.e. 13 % more than with the conventional ignition.

The improvement of the EGR tolerance in the other operating points is similarly positive. Besides an in general considerably shorter ignition delay, the burning duration is on average shorter in the case of a high-frequency ignition, as a precise analysis of the mass conversion points shows. The ignition delay is generally 5 to 20 °CA shorter, with a rising trend as charge dilution progresses. In terms of the combustion time (5 to 90 % conversion), the advantage compared with the conventional ignition is approximately 5 to 10 % (2 to 3.5 °CA), even if the mixture is highly diluted, and this leads to immediate advantages in terms of efficiency.

Behaviour at High Ignition Pressures and under Full Load

It is known from the literature that the spatial extension of the corona discharges scales inversely with the gas pressure - but less strongly than it would in the case of inverse proportionality [1, 3]. Therefore, a sufficient corona size at high ignition pressures is crucial as this would allow the volume ignition character of the high-frequency ignition to be used in high load points too. This requirement can be easily met in the present state of development of the EcoFlash ignition system. The specific advantages of volume ignition can thus also be combined unrestrictedly with high pressures



Potentials for the development of combustion processes using corona ignition

during ignition.

It has already been said elsewhere [1] that, in the case of the 1.4-l turbocharged engine equipped with an EcoFlash ignition system, it is possible under full load to shift the 50 % mass fraction burnt point up to 4° CA earlier in comparison with a transistor ignition at the same engine knocking intensity. This allows the mean pressure to be increased by 0.5 bar without the necessity of further design measures. Alternatively, it was possible to add up to 4% external EGR under full load while maintaining the maximum torque achievable with a 90 mJ transistor ignition system and thus to reduce the exhaust gas temperature by 10 K and the specific consumption by 2 %.

On the basis of these results, it is possible to reduce the enrichment under full load and – as a result of the more rapid ignition and the higher knock resistance – to increase the torque at low engine speeds. This has already been demonstrated in tests conducted with development partners and customers [7, 8].

Engine Endurance Test

In a high-load engine endurance test of the 1.4-l turbocharged engine lasting for more than 500 h, the constancy of significant operating parameters of the high-frequency ignition such as the power input and the mean frequency of the igniters over time was examined. The endurance test was interrupted at regular intervals and the wear on the ignition electrodes was documented. The parameters of the ignition system did not show any significant systematic changes over the operating time; the low wear on the tips of the electrodes also allows us to expect a lifetime in the vehicle of considerably more than 100,000 km.

Conclusions and Outlook

This article explains system layout and basic principles of the high-frequency or corona ignition and documents the advantages of the technology via test bench results. These tests showed an increased EGR compatibility, an improved knocking behaviour and thus also an improved specific consumption – even in the absence of any special geometrical modifications of the combustion chamber.

In conjunction with the many tests conducted on the EcoFlash ignition system with customers and development partners, we now have a clear picture of the possibilities and degrees of freedom which corona ignition has newly introduced into the development of combustion techniques: The volume ignition characteristics of corona discharges not only pave the way for high-EGR and lean combustion techniques – they also allow special concepts such as the minimisation of gas exchange losses via reduced charge motion or the efficiency improvement via Miller valve timing.

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