

Ignition Systems for Spray-Guided Stratified Combustion

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ABSTRACT

The success of stratified combustion is strongly determined by the injection and ignition system used. A large temporal and spatial variation of the main parameters - mixture composition and charge motion - in the vicinity of the spark location are driving the demands for significantly improved ignition systems. Besides the requirements for conventional homogeneous combustion systems higher ignition energy and breakdown voltage capability is needed. The spark location or spark plug gap itself has to be open and well accessible for the mixture to allow a successful flame kernel formation and growth into the stratified mixture regime, while being insensitive to potential interaction with liquid fuel droplets or even fuel film. For this purpose several different ignition concepts are currently being developed.

The present article will give an ignition system overview for stratified combustion within Delphi Powertrain Systems. In addition to conventional high energy systems, MultiCharge systems and their derivatives as well as more sophisticated advanced concepts are presented. Their potential for stratified systems is assessed in view of sometimes contradicting requirements like energy level vs. electrode erosion.

INTRODUCTION

Fuel economy has globally become the major development driver for new propulsion sources for passenger cars and light duty vehicles. Gasoline vehicles are still dominating the world market, nevertheless strong efficiency improvements are required to reduce the gap with Diesel engines. The introduction of vehicles with gasoline direct injection (GDI) reduces the current gap to Diesel-engine-powered vehicles. The first vehicles with spray-guided combustion systems are coming especially close [1]. When comparing engines of the same peak power, some of these stratified engines are already at the Diesel CO₂ emission levels.

Similar to the Diesel combustion the lean, stratified combustion in spark-ignited gasoline direct injection engines produces fuel savings for several reasons. First, unthrottled operation allows for a significant pumping loss reduction, especially at lower loads. Secondly, a gasoline engine with direct fuel injection can operate with a higher compression ratio yielding efficiency advantages. Third, the lean mixture being compressed has a higher ratio of specific heats. This allows for a more efficient compression and expansion process [2]. Engines with spray guided combustion systems need a centrally-mounted direct injector with preferably a hollow-cone spray. The spark plug is mounted in close proximity to the injector and positioned such that it is able to ignite a fuel-rich “recirculation zone” created by vortices just

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outside the spray cone. In order to produce the desired spray characteristics in the cylinder, currently a rail pressure typically in the range of 200 bar is used. For engine-out NO_x emission reduction a high amount of exhaust gas recirculation is required. From an exhaust emissions perspective, a key sub-system that must be added is the lean NO_x aftertreatment, typically in the form of a Barium or Potassium based NO_x storage catalyst (NSC).

One of the key challenges for the combustion system is to establish a robust repeatable mixture regime at the ignition location. This has to work in a wide engine speed and load range in order to maximize the efficiency benefits from stratified operation while minimizing the risk of misfire and partial burn cycles. The dominating role of the first combustion phase which is obviously closely linked to the injection and mixture formation process is therefore object of many investigations [3, 4, 5]. The majority of these activities are experimentally and often linked to the specific combustion system challenges. The present article will focus more on ignition system aspects rather than on mixture formation although both cannot really be separated for a successful stratified operation. It gives an overview on ignition system developments for stratified combustion systems within Delphi Powertrain Systems.

SPARK IGNITION AND STRATIFIED COMBUSTION PROCESS

In a regular SI combustion cycle the start of combustion is triggered by the spark breakdown which takes place between the electrodes of the spark plug after the ignition pulse has been applied. The high voltage is creating a strong electrical field between the electrodes that is strong enough to generate a highly conductive thin plasma channel ($\varnothing < 50 \mu\text{m}$) after the breakdown. Free electrons in the electrode gap are accelerated and collide with gas molecules, ionizing them and creating further “new” free electrons, which lead to an exponential increase of electrons like in an avalanching process. The plasma temperature after the breakdown of up to 60.000 K is cooling down by expansion within a few μs to values in the following arc phase of less than 10.000 K. In the final glow discharge phase the temperature of the plasma drops further down and the spark itself extinguishes with characteristic voltage oscillations when the feeding energy in the ignition system is becoming too low.

Due to convection processes of the expanding hot plasma in the spark channel the neighborhood of the gas/fuel mixture is heated up, where the first radicals are formed that are triggering the start of combustion, the so-called flame initiation. The local mixture composition expressed by the A/F ratio and the local temperature determine the laminar flame speed which is governing the flame kernel formation and flame kernel growth. The turbulence structure controls the spatial homogeneity of the mixture and temperature in front

of the flame zone and therefore indirectly the rate of the flame kernel growth. When the flame kernel size reaches a characteristic size of a few millimeters the macroscopic mean flow in the combustion chamber and the turbulence intensity are becoming the dominating variables in the turbulent flame propagation, which governs the major part of the premixed combustion phase.

In stratified combustion systems only a part of the entire combustion chamber volume is occupied by the premixed charge of varying A/F ratio while the remaining rest consists of fresh air and residuals. In principle the combustion steps are the same as for homogeneous combustion described above but limited to the stratified regime, which is temporarily and spatially determined by the injection process itself, the interaction with the combustion chamber and the overall flow pattern. In the combustion chamber of spray-guided systems the injector and the spark plug locations are closely located to each other and the flame initiation is only possible after combustible mixture has reached the vicinity of the spark gap. Due to this close timing relation the geometrical arrangement is essential for a successful and robust flame initiation and the following flame kernel development period. The first part of the combustion (inflammation) consists of the flame initiation and flame kernel growth, [Figure 1](#). At stratified operation the strong temporal and spatial gradients of the air-fuel charge caused by the closely timed injection process are becoming in addition a major contributor to the cyclic variations in a real engine environment [6].

<[figure 1](#) here>

The variability of the injection process itself causes the spatial and temporal variability of the mixture quality and flow pattern and generally tends to increase the overall cycle-to-cycle variations. The diffusive character of the mixture plume is introducing an additional strong time dependency. If the time between injection and combustion is too long turbulent diffusion processes are increasing the incombustible mixture zones with a too high A/F ratio and/or a too much diluted mixture composition. As soon as a flame kernel in a stratified combustion system has been successfully established the probability of a misfiring cycle is extremely low [4]. Partial burn can even be stronger when parts of the mixture regime can not be reached by the flame front due to separation and isolation. This can be caused by the injection process itself (e.g. due to temporarily separated multiple injections or by the turbulent interaction of the mixture plume with the in-cylinder flow) or also by flame expansion effects. Such an unfavorable mixture distribution can also result from a sub-optimal spray characteristic like a multi-hole injector with desultory mixture regimes from individual spray plumes can produce [7].

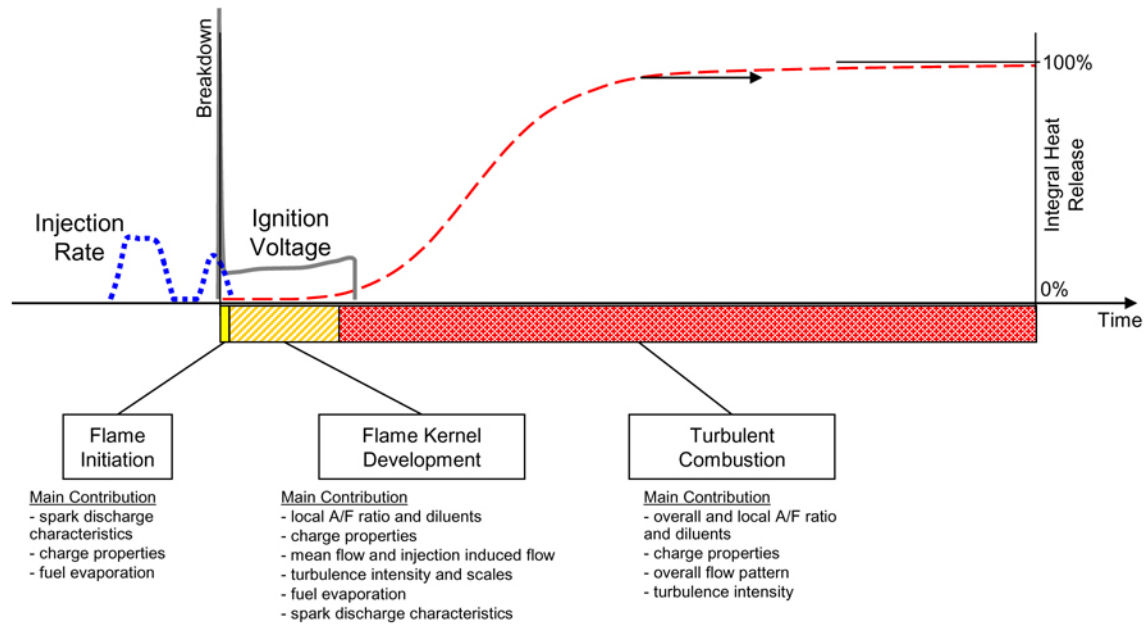


Figure 1. Schematic Representation of Injection, Ignition and Combustion at Stratified Operation

For acceptable cycle-to-cycle variations all major components and their interfaces have to contribute with only small individual variations to the overall combustion system. The tolerance requirements due to the stratified nature of the combustion regime are therefore quite high and consequently costly compared to homogeneous combustion systems.

THE CHALLENGE OF GASOLINE DIRECT INJECTION FOR IGNITION SYSTEMS

The above described in-cylinder conditions are underlining the specific demands for the ignition system to enable successful stratified combustion. Among the most challenging boundary conditions within a combustion chamber are wetted gap electrodes, high gradients of velocities and improper mixtures with residual liquid fuel droplets. They are determining the requirements for the key ignition system parameters, the peak voltage capability, the ignition energy and the capability for multiple ignitions. The remainder of this paper will focus on the electrical parameters of the ignition system (exclusive of spark plug design).

INTERACTION BETWEEN SPARK AND IN-CYLINDER STATE DURING STRATIFIED OPERATION

In the following the interaction between the stratified engine in-cylinder environment and the ignition system is described, highlighting the four effects that finally determine the ignition system requirements.

In-cylinder flow motion

The charge motion in the proximity of the spark gap is induced by either the flow motion of the ingoing air or the so-called entrainment flow generated by the injected fuel mass. It can expand the arc significantly into the combustion chamber. Figure 2 is illustrating the impact of the flow on the burn time and the burn voltage. The undisturbed spark, left side, burns much longer (green curve) compared to the same spark within a flow field, right side. The flow is stretching the arc, causing a longer arc channel with higher line resistance. The longer channel corresponds to a higher arc resistance leading to a higher burn voltage (blue curve) and a shorter burn time. At very high flow speeds induced by the injection plume the spark can even be extinguished.

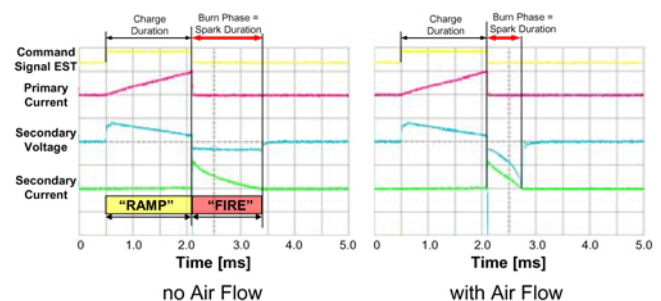


Figure 2. Influence of In-Cylinder Flow on Spark Duration and Burn Voltage

Liquid fuel phase around the spark plug

The presence of fuel droplets is unavoidable due to the short mixture preparation time and the reduced temperatures induced by the spray cooling. Due to different dielectric

constants of liquid and gas the E-field is lower in the liquid portion and the arc channel tends to follow the boundary layer on the surface of the droplets. Both the specific heat of liquid fuel that is significantly higher than of gaseous fuel and the evaporation energy contribute to a cooling of the arc resulting in a higher burn voltage demand. [Figure 3](#) shows the influence of the presence of liquid fuel droplets close to the spark plug on the burn voltage (blue curve). In the shown example the burn voltage is jumping several times from a usual level of between 500 V and 1 kV to values close to 5 kV. The effect observed here is believed to be not a result of any in-cylinder flow phenomenon or spray induced charge motion. In such cases the burn voltage pattern should be much smoother, like for instance on the right side of [figure 2](#). Fuel droplets entering the area of the burning arc in the spark gap, in turn, are discrete events that lead to the characteristic spike excursions of the burn voltage like marked in the red ellipses of [figure 3](#). In worst cases, the spikes can be even higher and lead to extinguishing the spark. It then depends on the remaining charge of the coil if the ignition system will be able to re-establish a spark or not.

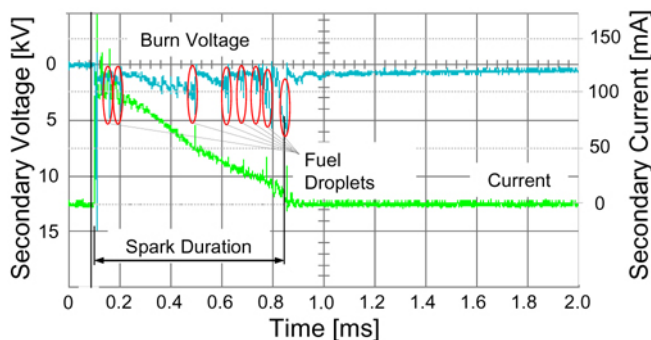


Figure 3. Injection into the Burning Arc. Burn Voltage Excursions due to Liquid Fuel Presence in the Plasma Channel

Higher compression ratios on GDI engines

It is well known that engines with higher gas densities at the spark event are showing a higher breakdown voltage demand. Unthrottled engine operation with a higher geometric compression ratio, typical for stratified engine operation, leads therefore to higher breakdown and shorter spark duration at part load. Boosted engine operation will further increase the breakdown voltage requirement.

Wet electrodes

Liquid fuel can build up thin films on the gap electrodes of a spark plug that are acting with the remaining air gap like stacked dielectric layers. Their relative dielectric constant ϵ_r and the - compared to air - considerably higher breakdown voltage of liquids lead to an overall breakdown voltage of the spark gap that can be considerably higher than in pure compressed air. High breakdown voltages bear the risk of a

surface discharge - a discharge channel developing along the surface of the insulator with potentially insufficient access to combustible areas of the mixture. This can lead to misfires.

PASCHEN'S LAW

Paschen's Law describes the required breakdown voltage in a gaseous environment [17], the relation between spark gap width, gas density and the gas composition itself. The empirical law does not conclude on the burn voltage after the breakdown. [Figure 4](#) shows this relationship in a heated gas stream of pressurized air. With increasing gas temperature the breakdown voltage drops but at the same moment the density is reduced, too. It is also clearly shown that the actual flow speed has almost no influence on the breakdown voltage since the actual breakdown takes place within a few nanoseconds during which the moving gas can be considered motionless ([Figure 4](#) right picture).

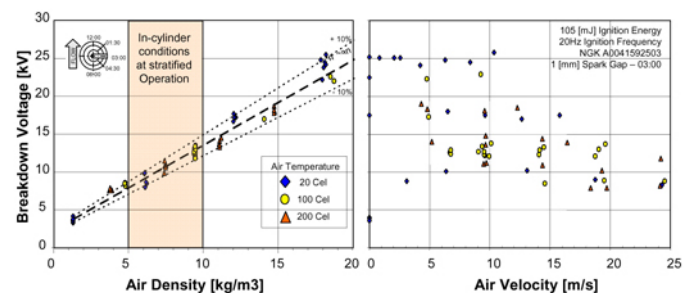


Figure 4. Breakdown Voltage as Function of Gas Density

IGNITION BURN TIME - SPARK DURATION

The burn time is a function of the stored energy in the coil. Since the stored energy E of the ignition coil is limited, a higher burn voltage - which represents a higher dE/dt - consequently leads to a shorter burn time until the coil has been completely emptied and the spark extinguishes.

The secondary coil and the arc across the spark plug gap are acting like a voltage divider consisting of the impedance of the coil and the variable impedance of the arc. The secondary starting current of the ignition transformer is given by its turns ratio. Simply spoken, if the resistance of the arc becomes high the burn voltage across the arc is increasing at the same ratio to maintain the current that the transformer equations require: Thus, the power $P = dE/dt$ is increasing.

The influence of the flow speed, in-cylinder pressure and temperature on the spark duration has been experimentally determined in an optically accessible tube with controllable air flow, pressure and gas temperature. It can be observed in [Figure 5](#) that with increasing density the spark duration is reduced even when the gas velocity is zero. This is to a