

Spark Ignition, Early Flame Development and Cyclic Variation in I.C. Engines

Gautam T. Kalghatgi

Shell Research Ltd.

Thornton Research Centre

ABSTRACT

Combustion and pressure development in spark ignition engines are marked by cycle to cycle variations which are especially severe if the mixture is lean. The variations in indicated mean effective pressure (IMEP) that arise from this could be sufficiently severe to cause problems in certain engine operating regimes even in engines which run smoothly at steady operating conditions. Cyclic variations in IMEP could be effectively reduced at source by reducing cyclic variations in combustion. These are known to originate during the initial stage of combustion which can be influenced by the ignition process. Of the various enhanced ignition devices, variants of the spark ignition system seem to be of most practical interest for automobile applications in the immediate future. In the paper, we review the literature on spark ignition, the nature of the spark discharge process and the attempts to improve stability of engine operation through changes in spark ignition.

COMBUSTION AND PRESSURE DEVELOPMENT in a spark ignition engine are marked by cycle to cycle variations which are particularly severe if the mixture is lean. This aspect of engine combustion has been studied extensively as reviewed by Young.[1]* Young[2] has also discussed the relationship between cyclic variations in combustion and those in indicated mean effective pressure (IMEP). In general, the normalised variations of IMEP are much smaller in magnitude than those of combustion that give rise to them because of the weak coupling between the two. Hence for a given engine it is easy to find a suitable steady operating regime where the IMEP variations are acceptably low. However, there

are many regimes of engine operation where the burning velocity is low and ignition and flame initiation are difficult and where for a given setting an engine could run into problems associated with excessive IMEP variations. For instance, such conditions could be encountered during

- (i) cold starting
- (ii) part throttle acceleration - when the mixture strength becomes momentarily leaner since the fuel flow rate does not increase as quickly as the air flow.
- (iii) idling - when the laminar burning velocity is low because the pressure and hence the temperature of the charge is low.

All these problems would become even more important if engine design trends move towards lean burn and high exhaust gas recirculation concepts.

Cyclic variations in IMEP can be reduced by:[2]

- (i) reducing them at source i.e. by reducing the combustion variations or by,
- (ii) Weakening the coupling between the combustion and IMEP variations. This can be achieved by arranging more energy to be released with the piston at around top dead centre by shortening the combustion duration and by suitably advancing the spark timing.

Thus this second approach requires new developments in engine design (e.g. fast burn engines) and/or more engine management in terms of such variables as spark advance. Reducing cyclic variations in combustion is a very attractive route towards improved stability in engine operation.

It has long been recognised and is now widely accepted that cyclic variations originate during the initial stage of combustion from the time of the spark breakdown to a "noticeable"

* Numbers in parentheses designate references at end of paper.

departure of the cylinder pressure from the compression pressure, (e.g. Refs. 3, 4 and 5). There are several models (e.g. Refs. 6, 7 and 8) that predict that, other things being equal, cyclic variations are reduced if the flame kernel reaches a critical size more quickly i.e. if early flame development rates are increased, and this inference is well supported experimentally (e.g. Ref. 9). Early flame development rate could be increased and hence cyclic variation reduced, chemically, by increasing the laminar burning velocity—for instance by running the engine rich (e.g. Refs. 3 and 10) or by reducing the exhaust residual mass fraction (e.g. Refs. 3 and 9) or by changing the fuel (e.g. Ref. 9 and 11). However, in practice these options do not really exist for reasons of fuel economy and acceptable exhaust emissions; moreover engines have to use normally available fuels.

The other well established way of improving this early phase of combustion is through the ignition process (e.g. Refs. 12 and 13), for instance by increasing the energy of the conventional spark [12-14] or by using other ignition systems such as plasma-jet ignitors [15,16]. In fact there has been considerable work done on enhanced ignition devices such as high energy spark plugs, plasma jet ignitors, flame jet ignition, torch cells, photochemical, laser and microwave ignitors and divided chamber stratified charge engines. A recent review of such devices has been published by Dale and Oppenheim [17]. However, of all these, the variants of the spark discharge system appear to be of the most practical interest for automobile applications in the immediate future. For instance, plug erosion and increased power consumption in the ignition system remain serious obstacles to widespread practical use of plasma jet ignitors [18,19] and the other devices are either speculative or require major changes in engine design.

In this paper we review the literature on the nature of the spark discharge process, spark ignition and the attempts to improve stability of engine operation through changes in spark ignition.

THE SPARK DISCHARGE PROCESS

The formation of a spark requires access to a large supply of electrons from electrodes [20]. A rapid procurement of electrons leads to the production of fresh ions and electrons in Townsend avalanches and proceeds as a transient discharge until a maintenance mechanism is established. This transition from a weakly ionised gas to a strongly ionised gas is what should be called a spark [21]. An externally applied electric field is required to maintain the discharge and the type of discharge that results upon spark breakdown of a gap depends on the gas pressure, gap length and shape, the nature of the applied voltage and the external circuit.

Typical static voltage-current characteristics of different types of discharge

are described in Ch. 8 of Ref. 22 and are shown in Figure 1. The first type of discharge, extending to beyond point A is the "dark" or Townsend discharge. If the applied voltage is increased, a point S is reached at which the spark gap breaks down and a spark results.

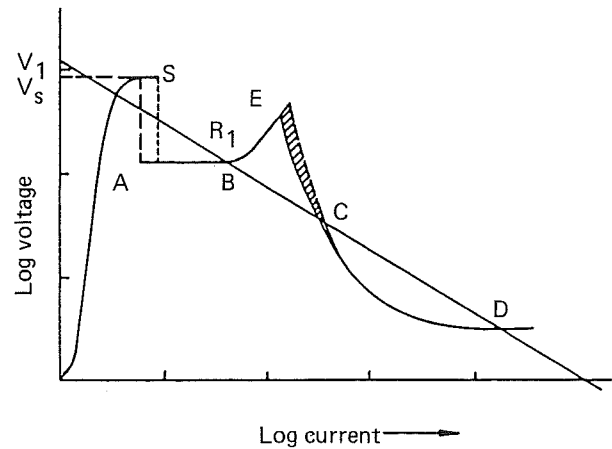


FIG. 1 — Discharge characteristics

The region between S and B is a normal glow discharge for which the voltage drop is nearly independent of the discharge current. When the current is increased beyond a critical value, the discharge voltage increases along B-E. This discharge is termed an "abnormal" glow. A further increase in the current results in a sudden transition to a low voltage discharge called the arc. The point at which this transition occurs is sometimes quite uncertain. The characteristics described above are idealised and the actual characteristics may be different from those shown in Figure 1, depending on the gas pressure, the gas and the electrodes.

The criterion for stability of the discharge, known as Kaufman's criterion, may be expressed mathematically as

$$\frac{de}{di} + R > 0$$

where de/di is the slope of the discharge characteristic at the point of its intersection with the resistance line. Thus in Figure 1, once breakdown has occurred, with an applied voltage of V_1 and a series resistance R_1 , the discharge described by point B or point D is stable whereas the one described by C is unstable. The presence of any inductance, L , in the circuit complicates matters somewhat and the discharge may then momentarily operate at unstable points [22]. The elementary phenomena that govern the electrical discharge process in gases can be considered under four heads: (a) the production of electrons and ions at electrode surfaces, (b) their production in a body of a gas, (c) their motion and (d) their recombination in the gas and

disappearance at the walls and electrodes. These subjects are discussed in all the standard text books on the subject (e.g. Refs. 22-26).

In practical coil ignition systems there is always a substantial inductance. Very simply, the system consists of a primary coil of

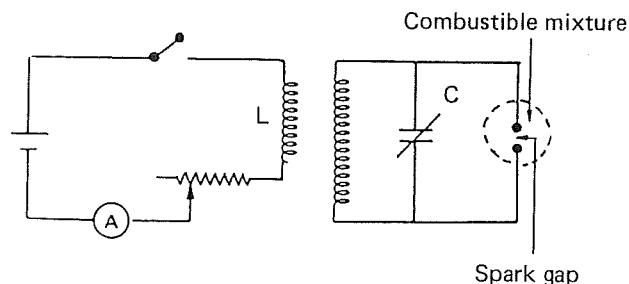


FIG. 2 - Typical, practical ignition system

inductance, L , (see Figure 2) with a current, i , flowing through it. When this current is interrupted, a voltage equal to $L di/dt$ is caused in the circuit. This, in turn induces in the secondary circuit containing the spark gap a voltage high enough to bring about a breakdown in the gap. Since the secondary circuit also introduces capacitance, the discharge in a practical system always contains capacitive as well as inductive components; breakdown is followed by an arc and a glow phase which may last upto 1.5 ms. We consider below, in slightly greater detail, the breakdown, arc and glow phases of the discharge. Maly has written an excellent review [27] on these topics and their relevance to I.C. engines and we draw substantially on that paper.

BREAKDOWN - Pre-breakdown Processes and Breakdown Voltage - Electrons move much more rapidly than positive ions because of their much smaller mass and hence in high pressure discharges almost all the current is carried by electrons. As the potential difference between electrodes is increased, first, the electrons liberated at the cathode will start reaching the anode as fast as they are produced and the current reaches a saturation level. At still higher voltages, the current rises above the saturation level as some of the electrons form additional electrons on colliding with atoms of the gas. This is referred to as an electron or a Townsend avalanche. As the potential difference is further increased, other processes such as secondary emission of electrons by the collision of positive ions with the cathode come into play and contribute to additional production of electrons. Eventually the current reaches a very large value and breakdown occurs. The breakdown voltage V_s is related to the breakdown potential E_s , in a uniform field, by $V_s = E_s/d$, where d is the spark gap.

The breakdown voltage is a function of pd , the product of pressure, p , and gap distance, and the gas in which discharge takes place. At high pressures (1 atm. and above), breakdown voltage is practically independent of the cathode

material [26]. However, the condition of the electrode surface is also extremely important in determining the breakdown voltage. For instance, at high pressures, breakdown voltage can be reduced substantially by roughening the electrodes with sand-paper. This is believed to be due to local space charge distortion and to local discharges preceding breakdown. The effects of roughening can be removed by prolonged sparking. The presence of gaseous impurities especially of electronegative molecules such as O_2 , SO_2 , the halogens and of water vapour results in an increase in breakdown voltage. In a dynamically increasing field such as that across the gaps of a spark plug in an I.C. engine, the inherent time lag, which precedes breakdown [26] could also influence the actual breakdown voltage.

A comprehensive review of breakdown processes and breakdown voltage characteristics can be found in Ref. 26.

Thermalisation of the Spark Channel and Energy Transfer Considerations - Heating of the gas has to be accomplished by transferring the energy from the applied field to the electrons and then from the electrons to the ions or neutrals because over the observed time scales over which breakdown takes place (about 40 ns), only electrons can account for any significant motion. However at this stage the electron concentration (about 10^{15} cm^{-3}) is too low to bring about any increase in the gas temperature. Further ionisation must take place which increases this electron density to about 10^{17} cm^{-3} [20]. This happens within about 40 ns. Although it is not clear exactly how this comes about, there is evidence for the existence of very rapid ionisation waves that propagate at a fraction of the speed of light and lead to breakdown. More recent work has shown that, in high pressure breakdowns, formation of a cathode spot of molten electrode material provides the required source of additional electrons [21].

Thus whenever a spark forms, a cathode spot is always present. These spots form very suddenly - within nanoseconds - and last for tens of nanoseconds. They are produced because dielectric material on the metal surface - present either as oxide layers or inclusions in metal structure - accumulates charge until a local explosion associated with the destruction of the whole surface takes place.

The temperature of the gas increases greatly - up to 40 000 K - in a very short time - of the order of 10 nanoseconds. This brings about an almost instantaneous increase in pressure to several hundred bar in the spark channel, causing the emission of an intense shock wave. However almost all the energy fraction ($\approx 30\%$) carried away by the shock is regained by the gas before the shock has travelled a few millimetres [27]. Radiation losses as well as thermal losses to electrodes are small and over 90% of the energy dissipated during the breakdown process is transferred to the gas [27].

Breakdown in Typical Automobile Ignition Systems - In conventional coil ignition systems,

the energy dissipated during breakdown is small (0.3 to 1 mJ) though the power level is very large - up to megawatts. The total energy dissipated during the whole of the spark event in a conventional ignition system is between 30 to 100 mJ. Thus only a small fraction of the total energy is delivered during the breakdown phase. The characteristics of the breakdown phase are determined by the capacitance, C, (5-15 pF) and the inductance (≈ 5 nH) of the spark plug and the spark gap and the peak current is determined by the breakdown voltage and the characteristic impedance of the near-gap circuit (usually of the order of 50 Ω) [27].

It is possible that under certain circumstances - for instance when the electrodes are contaminated by oil or deposits - the breakdown voltage is not attainable by the ignition system and the spark does not fire.

ARC DISCHARGES - The breakdown phase creates a channel of high conductivity through which a self-sustained discharge like the arc can take place. Typically, in an engine it is characterised by currents in excess of 100 mA with the upper limit determined by external electrical impedance. It usually lasts for a few micro seconds and is caused by the discharge of the capacitance of the high voltage leads and the coil. The arc voltage is low - about 50 V [27]. This burning voltage of the arc can be divided into three distinct regions - the cathode drop region, the positive column and the anode drop region.

The cathode drop region is one of very high positive-ion space charge and is confined to a very short distance in front of the cathode. The voltage drop in this region is of the order of the least ionisation potential of the gas or vapour in which the arc burns. The positive ions in this region bombard the cathode and the energy released by these produces very high temperatures at the cathode which inevitably leads to the formation of cathode spots of molten electrode material. Indeed, the electrons needed to sustain the arc are supplied from these cathode spots and any measure which leads to quenching of these spots leads to the extinction of the arc. Considerable amount of material is lost because of these cathode spots - the erosion rate being dependent on the boiling point and conductivity of the electrode material; this topic has been studied by Llewellyn-Jones [49, 50].

In the high pressure arc, the positive column is at a very high temperature ~ 6000 K. The positive column in most cases has a well defined boundary. A high temperature gradient - of the order of several thousand degrees per millimeter - exists in the region immediately surrounding the arc core. The voltage gradient, $\Delta V/\Delta d$, in the positive column is related to the current, i , by an equation of the form

$$\frac{\Delta V}{\Delta d} = B i^{-n}$$

where B and n are constants which depend on the electrode material [28]. In high pressure arcs,

the anode temperature is equal to or greater than that of the cathode and is limited to the boiling point of the material. The voltage fall in the anode drop region is of the same order as the cathode fall.

In a typical coil ignition system, the arc phase accounts for about ten percent of the total energy released in the spark. The energy dissipated in the cathode and anode fall regions is mostly lost to the electrodes and only about 50% of the total electrical energy dissipated in the arc is available for transfer to the gas through the positive column [27]. This energy transfer is due to heat conduction and mass diffusion and is more inefficient, the further the surface to which energy is being transferred is from the core of the arc.

THE GLOW DISCHARGE - The high pressure glow discharge is very similar to the arc except for a cold cathode. The glow discharge maintains itself by virtue of the secondary electrons which are liberated at the cathode by the impact on it of positive ions. This is an inefficient process and only low currents (<100 mA) can be sustained. High pressures as well as the presence of low work function materials on the cathode increase the tendency of the glow discharge to change into an arc.

The burning voltage for a glow is much higher than that for the arc (≈ 500 V) and consists of the cathode and anode falls with the voltage gradient in the positive column in between. The cathode drop is much higher than in the arc and depends on the gas in which the discharge takes place as well as on the cathode material. The presence of low work function materials on the cathode leads to a dramatic reduction in the cathode fall (Ref. 22, p.216). The bombardment of positive ions causes a continual disintegration of the cathode surface which is called sputtering. The loss of electrode material thus caused, is small, especially in comparison with the arc. In engine like conditions, the positive column has a temperature of the order of 3000 K [12, 27] and as in the arc, forms the main region from which energy is transferred to the gas. As in the arc, the anode fall is caused by the electron space charge near the anode and is of the same magnitude as in the arc.

The losses to the electrodes are much higher in the glow discharge mainly because of the large cathode fall. This energy lost in the electrode drop regions depends on the electrode material and has been estimated to decrease as the electron work function of the cathode material decreases [28]. Deposits of low work function materials on the electrode should also bring about a decrease in the energy lost to the electrodes because they reduce the cathode fall. Maly estimates [27] that at best 30% of the electrical energy dissipated in a glow discharge is available to heat the gas.

In a conventional coil ignition system, the glow discharge accounts for most of the energy ($\approx 90\%$) released by the ignition system. This is the phase during which the main energy storage

device - the coil - dumps its energy into the discharge circuit. It lasts for a long time - over 1 ms, but is the least efficient of the three modes in transferring electrical energy to the gas.

Figure 3, based on the discussion in Refs. 12 and 27, summarizes the current and voltage characteristics of the discharge from a typical coil ignition system.

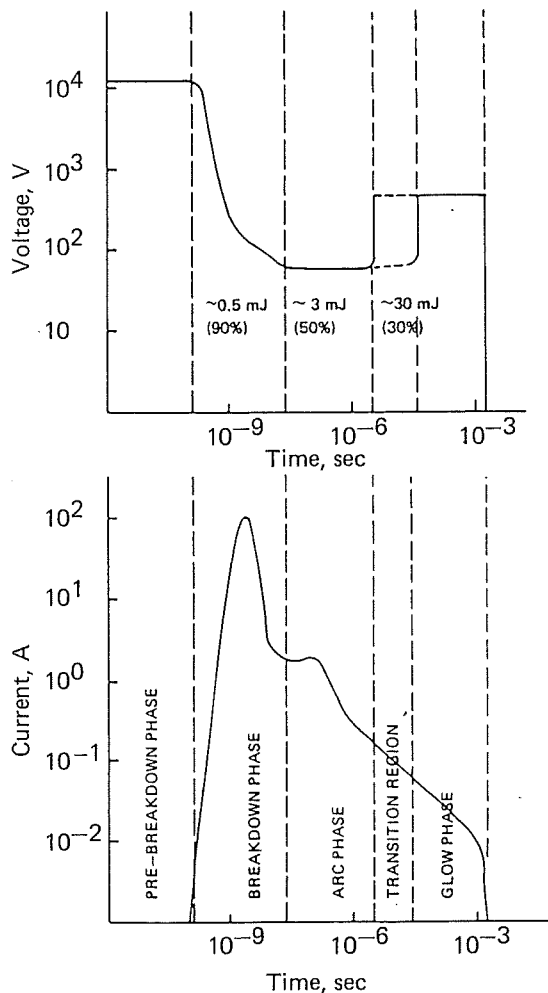


FIG. 3 - Variation of voltage and current with discharge time for a typical coil ignition system, after Refs. 12 and 27. Typical values of energy and energy transfer efficiency (in brackets) are indicated for each phase in the upper half of the diagram

SPARK IGNITION

It has long been known that it is possible to pass small electric sparks through an explosive gas without producing ignition [29] - the spark energy needs to be raised to a threshold level known as the minimum ignition energy before the spark sets off a propagating combustion wave. It has also been known that the rate at which the electrical energy is supplied and the nature and configuration of the

electrodes are important. There have been several theoretical attempts to describe the general ignition problem in thermal terms - considering only the heat release and flame propagation aspects without taking into account diffusional factors (see, for example, the review by Merzanov and Averson [30]). Some of these studies have incorporated fairly complex chemical kinetic schemes (e.g. Ref. 31). Spark ignition has also been described in such broadly thermal terms for quiescent as well as flowing mixtures [32-36]; all these theories lean heavily on the intuitive original concepts of Lewis and von Elbe [29]. More recent models borrow ideas from techniques using activation energy asymptotics and put the spark ignition problem on a sounder theoretical footing [37-40]. However, practically useful knowledge about spark ignition has been mostly derived from experimental studies (e.g. Refs. 41-54) which have largely concentrated on the critical conditions needed to bring it about. We outline below the theoretical concepts and briefly discuss the important experimental findings.

THEORETICAL CONCEPTS - Ignitions are essentially heat transfer processes and their onset takes a long time compared to the time for an electrical breakdown of the gas between the electrodes [20]. In the first instance the spark must raise the temperature sufficiently in a small volume round the discharge channel to cause a thermal runaway [30]. When this approximate 'ignition criterion' is fulfilled chemical reaction starts consuming the reactant and the combustion wave starts to propagate outward [38]. In order to continue to propagate, the flame should have grown to a critical size by the time the temperature at the origin has decreased to around the normal flame temperature. If the flame size is less than this critical size, the rate of heat release within the inner zone of chemical reaction is insufficient to compensate for the rate of heat loss to the outer zone of pre-heated unburned gas so that the temperature decreases throughout the reaction volume. The reaction gradually ceases and the flame becomes extinct after only a small amount of gas around the original spark channel has burned. In order to drive the flame kernel beyond the critical size, the spark energy input must also fulfil some 'initiation criterion'. If the spark channel size is less than this critical kernel size, flame initiation may require much stronger conditions than those needed just for ignition [38, 40]. A flame of this critical size is also referred to as the minimal flame [29].

Excess Enthalpy - Lewis and von Elbe [29] invoked the concept of "excess enthalpy" to explain the existence of a minimum ignition energy. According to their hypothesis, all combustion waves possess excess enthalpy whose role is to maintain a proper slope of the temperature gradient so that a balance is maintained between the heat flow into the pre-heat zone and heat liberation in the reaction zone. For flame sizes smaller than the critical size there is not enough burned gas in the core

to supply the required excess enthalpy and energy must be supplied from an ignition source. Thus the minimum ignition energy is equal to the excess enthalpy requirement of the minimal flame. Though this hypothesis is useful in explaining experimental observations, its validity has been questioned [32] and indeed, Lewis and von Elbe themselves recognised that it was unprovable [29].

The Minimal Flame and Flame Stretch - The idea of a minimal flame can also be explained in terms of 'flame stretch'. A flame sheet is very sensitive to stretching because it alters the gradients of heat and active species flux at the flame front in such a way that flame temperature as well as flame speed is lowered (p.227, Ref. 29). There is a maximum flame stretch rate above which a flame that is not supported by an external heat source, will be extinguished. Lewis and von Elbe had to postulate this but recent theoretical work using activation energy asymptotics reveals this explicitly (e.g. Ref. 55).

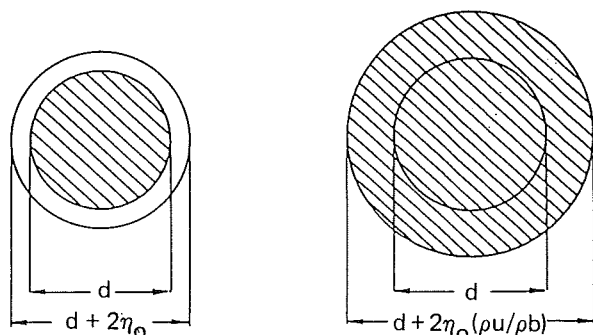


FIG. 4 - Increase of flame diameter on burning a shell of thickness η_0

Consider a spherical flame of diameter d within a thin shell of unburned gas of width η_0 (see Figure 4). The shell expands on burning because the density decreases from ρ_u to ρ_b . If η_0 is small compared to d , the width of the shell after burning becomes $\eta_0 (\rho_u/\rho_b)$ and the ratio of the spherical surface before burning to that after burning is $1 + 4(\eta_0/d)$. The flame stretch factor is given by $4(\eta_0/d)(\rho_u/\rho_b)$. Thus if the diameter of the flame is small, the flame stretch factor will be large and if it is larger than the critical value, the flame will be quenched.

Recent theoretical analyses [37-39] of ignition assuming spherical symmetry explicitly predict, for each mixture, the existence of a critical radius which the flame must reach, aided by the heat source, before it may continue unsupported. The minimum energy for ignition increases with this critical radius. Such theoretical studies are of much value in assessing the relative importance of different factors affecting flame initiation and in explaining, at least qualitatively, many of the experimental observations. However, none of the theoretical treatments so far, adequately take

into account the profound effect of electrodes, through quenching and modification of the spark discharge process, on the ignition process. Most of the practical information on spark ignition, is, in fact, derived from experimental observations.

EXPERIMENTAL RESULTS - Most of the experimental work on ignition has been done with capacitance sparks. Very briefly, in such an arrangement, two electrodes with a gap, d , between them are placed in the combustible mixture with a condenser of capacitance C connected in parallel. When the condenser is charged to a voltage V equal to the breakdown voltage of the gap, the condenser will discharge as a spark across the gap. The total energy $\frac{1}{2} CV^2$, stored in the condenser will be dissipated at the gap and except for possible losses will be available for ignition. The main loss is due to quenching at the electrodes though some energy also radiates away from the spark gap in the form of a shock wave.

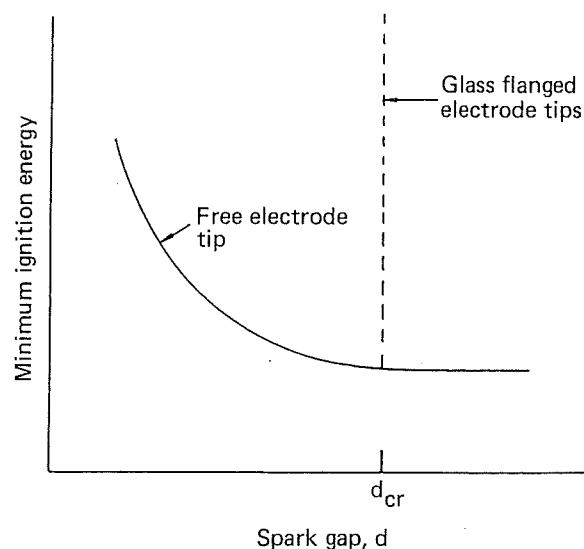


FIG. 5 - Variation of minimum ignition energy with spark gap

Quenching and the Spark Gap - The results of the pioneering experiments of Lewis and von Elbe [29] which showed the quenching effect of the electrodes, are illustrated in Figure 5, where the variation of minimum ignition energy with the spark gap has been shown for a given mixture. The solid line is for free plain hemispherical electrode tips whereas the broken line shows the results when the tips were flanged with relatively large glass discs. It can be seen that the glass discs almost completely suppress ignition when the gap is reduced to a critical value. This critical distance is the quenching distance and it is a property of the mixture.

Later experiments by Rose and Friede [43] showed that as the spark gap is increased beyond the quenching distance, the minimum ignition energy does not remain constant as Lewis and von

Elbe found, but increases slightly for sharp (0.2 mm diameter) electrodes. Rose and Priede [43] also found a marked effect of the electrode size on the minimum ignition energy; the results obtained from 1 mm and 10 mm diameter electrodes were quite different from those obtained with 0.2 mm diameter electrodes. They explained these observations in terms of differences in the spark discharge characteristics such as discharge time and peak current, with different electrodes.

Effect of Pressure - Increasing the pressure markedly decreases the minimum ignition energy; for example for a stoichiometric mixture of methane and air, minimum ignition energy decreases by more than a factor of twenty if the pressure is increased from 0.1 atmosphere to 1 atmosphere [29].

Effect of Mixture Composition - When the minimum ignition energy is plotted against the fraction of the fuel in the mixture, the curve has a minimum. For mixtures of different hydrocarbons with air, the minima of these minimum ignition energy curves occur at nearly identical energy values. However the minima shift to richer-than-stoichiometric mixtures as the number of carbon atoms in the fuel increases (see Figure 163, Ref. 29). For instance, at atmospheric pressure, for methane, the minimum in the minimum ignition energy curve occurs at a concentration of 0.9 times stoichiometric whereas for heptane, it occurs approximately at 1.8 times stoichiometric. This is explained by the lower diffusivity of the higher hydrocarbon molecules. In the strongly curved minimal flames, preferential diffusion of the more readily diffusing component of the mixture produces a significant enrichment of that component - for instance, of oxygen in preference to the higher hydrocarbon molecules (p.344, Ref. 29 and also Refs. 37 and 39). To counteract this effect, the less diffusive the fuel, the richer the mixture should be to have the minimum ignition energy.

The presence of diluents with a large heat capacity such as carbon dioxide or large heat conductivity such as helium, also contributes to quenching of the minimal flame and leads to an increase in the minimum ignition energy (Figures 164 and 165 in Ref. 29).

Effect of Electrode Material - Rose and Priede [43] found that for a hydrogen-air mixture (50% hydrogen), the minimum ignition energy decreased with the electrode material in the order of platinum, aluminium, silver and cadmium. The explanation that they advance for this observation is that only a proportion of the electrical energy that is released at the spark gap contributes to the ignition process, since some energy is lost to the electrodes. In these arc discharges this energy is spent in bringing a critical area of the electrode material at the cathode and anode spots to its boiling temperature. A qualitative estimation of such losses based on Llewellyn-Jones' theoretical work [49, 50], did show that the greatest loss is to be expected for platinum with the losses to aluminium, silver and cadmium following in that order [43]. Ballal and Lefebvre [47] also found

that in flowing gases the energy required to bring about spark ignition was appreciably reduced by using electrode materials with low conductivity and low boiling temperature e.g. cadmium electrodes were better than tungsten electrodes. Ziegler et al. have also found a similar correlation between minimum ignition energy and the boiling temperature of the electrode material [28] but they explain such differences in minimum ignition energy in terms of differences in the electrode materials which result in differences in the cathode fall during the glow discharge and hence the energy lost to the electrodes.

Effect of gas flow - If the gas flow around the spark is laminar, minimum ignition energy decreases with increasing flow velocity, [13, 51] up to a limiting velocity. This is because the flow carries the incipient flame away from the quenching effect of the electrodes. Consequently this effect is stronger for thick electrodes, small spark gaps, and weak mixtures where such quenching is important [13].

In most practical systems the gas flow around the spark is turbulent and it is well established that minimum ignition energy increases markedly with increasing turbulent intensity (e.g. Refs. 13, 33, 34, 36, 44 and 46). This has been explained mainly in terms of the effect of turbulence on transport processes which lead to an increased flame front thickness and the corresponding increase in the initial critical volume in which ignition energy is to be released [13, 36]. A secondary effect is due to an increase in heat dissipation and the consequent decrease in the efficient fraction of spark energy available for ignition. Both these effects are dependent on the intensity as well as the scale of turbulence. However, if the laminar flame thickness is equal to or smaller than the scale of the smallest eddies (Kolmogorov length scale) as is true in a high pressure system such as the spark ignition engine, turbulent mixing is not important and the dominant mechanism by which the fluid motion quenches the flame is by turbulent straining [8, 46]. It has also been established that the flow round the electrodes alters the nature of the electric discharge (e.g. Refs. 13, 54 and 56). Thus turbulent flow has a quenching effect on the flame though this is alleviated to some extent by the fact that the flow also convects the incipient flame kernel away from the quenching effect of the electrodes.

Effect of the Duration of the Spark - It is almost impossible to get a purely capacitive discharge in practice since there will always be some stray inductance and resistance distributed throughout the circuit in leads, connections, electrodes etc. [52, 53], which can significantly affect the variation of the discharge current with time.

Rose and Priede have investigated the effects of changing circuit parameters such as the resistance on the nature of the discharge [53]. They found that minimum ignition energy decreases with increasing duration of discharge,

which can be brought about by increasing the series resistance. They concluded that ignition is affected not only by the time intervals during which the spark channel remains in a conducting state but also on the voltage level at which the energy is being released, as well as on the diameter of the spark channel; all these factors are dependent on the circuit parameters [43].

The effect of the duration of the discharge on minimum ignition energy has also been studied in bomb experiments by Kono et al. [45, 48], DeSoete [13] and Maly and co-workers [12, 28]. Swett [34] and Ballal and Lefebvre [47] have investigated this aspect of ignition in flowing mixtures. Effects of such spark parameters on engine operation at high exhaust gas recirculation rates [57], as well as in lean burn conditions (Refs. 58-61) have been reported.

Kono et al [45] found that optimum spark duration was between 50 μ s and 300 μ s depending on the mixture strength and quenching action of electrodes; when quenching is significant as with small electrode gaps, thick electrodes and weak mixtures, the optimum spark duration is larger. This is also confirmed by DeSoete's experiments [13]. Engine experiments suggest that at high exhaust gas recirculation rates and lean conditions, long duration sparks lead to better engine operation [57, 60, 61]. However Maly and co-workers have studied the discharge process in detail and have argued that the best results for ignition are obtained if the spark energy is concentrated in the very short duration breakdown component (Refs. 12, 27, 56, 58).

Effect of the Nature of the Spark - Ziegler et al. [28] and Kono et al. [48] have shown that ignition ability is higher i.e. minimum ignition energies are lower for arc discharges compared to glow discharges. This is because a higher proportion of the spark energy is lost to the electrodes (mainly cathode) in a glow compared to an arc as discussed in Section 2.

Summary - Two separate criteria have to be fulfilled in order to successfully initiate a flame in a premixed mixture by a local input of thermal energy such as by an electric spark [38]. An ignition criterion which is to raise the local temperature enough to cause thermal runaway and start the chemical reaction and a more demanding initiation criterion which requires the amount and duration of the energy input to be sufficient to drive the flame kernel beyond a critical size. Thus there is a minimum energy that needs to be supplied by the spark to bring about successful flame initiation and this depends on the characteristics of the mixture e.g. composition and pressure, as well as on the flow field around the spark. It also depends critically on the duration and nature of the discharge as determined by such things as circuit parameters, electrode shape and size, spark gap, electrode material and the flow around the electrodes.

In the next section we discuss early flame development and the causes of cyclic variations.

EARLY FLAME DEVELOPMENT AND CAUSES OF CYCLIC VARIATION

EARLY FLAME DEVELOPMENT - Even in quiescent conditions, a flame that is initiated by a spark takes a certain time to reach a steady velocity corresponding to the laminar burning velocity of the mixture. The flame velocity before this steady state is reached could be higher or lower than the final value depending on the nature and the strength of the spark [12-14]. In turbulent flow conditions such as in an engine, this flame development phase is affected by turbulence and the "fully developed" flame velocity depends on turbulence parameters such as turbulence intensity and length scale as well as the laminar burning velocity. Abdel-Gayed et. al. [62] have argued that the relevant time scale for this growth period is the lagrangian time $t_L = 0.44 l/u$ where l is the integral length scale of turbulence and u , the r.m.s. turbulent velocity. Their analysis suggests that the flame velocity reaches 93% of its fully developed value at a time $2 t_L$ after ignition.

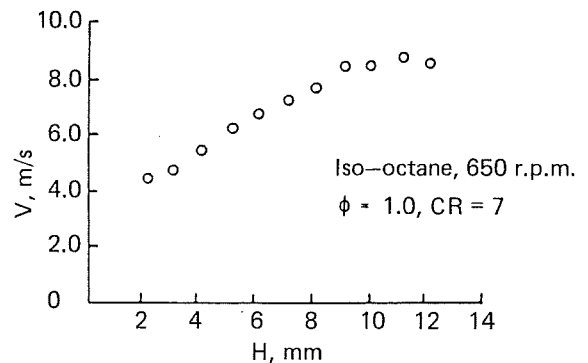


FIG. 6 - Example of the evolution of mean flame speed with distance from spark plug in an E6 engine

Flame velocity during this early phase has been measured in an engine using a laser technique in Refs. [9] and [10] and from pressure measurements and schlieren photography in Ref. [63]. A typical example of the development of average flame velocity with distance from the spark gap, during this early phase taken from Ref. 9 is shown in Figure 6. Each point shown in Figure 6 is calculated from an ensemble average of flame travel time across two laser beams spaced 2.5 mm apart and based on around 1500 engine cycles. During this early phase - before the flame radius has reached about 12 mm - typically, less than about 2% of the charge is burnt so that there is no significant pressure rise due to combustion. Hence this phase is sometimes described, misleadingly, as ignition delay.

In the particular engine from which the result in Figure 6 is obtained, the ensemble mean flow velocities are small and the evolution of the average flame velocity with distance from the

spark gap happens to be essentially spherically symmetric and centred at the spark gap [9]. Of course, this does not mean that the flame develops as a sphere centred at the spark gap every single cycle. Indeed, it is the variation in flame development from cycle to cycle during this phase that is predominantly responsible for cyclic variation in pressure development. We discuss below the causes for this variation.

INFLUENCE OF THE FLOW FIELD ON EARLY FLAME DEVELOPMENT - When the flame kernel is small, it is more likely to be moved around bodily by the flow as shown recently by Beretta et al. [63] in engine experiments. Similarly, Akindele et al. [36] have noticed convective velocities of the flame kernel close to r.m.s. turbulent velocities in bomb experiments on ignition of turbulent mixtures. Such convection has a significant effect on pressure development through its effect on the overall flame surface area later in the cycle as elucidated by the models of Keck and co-workers [63, 64]. For instance conditional sampling experiments [10, 65] have shown that if the flow near the spark plug near the time of spark break down is directed towards the engine wall, the peak pressure reached is low and vice versa, presumably because in the former case part of the flame surface will be quenched by the wall as the flame kernel is convected into the wall.

The turbulent flow also imposes an external strain field which reinforces the inherent strain experienced by the flame front of an expanding flame kernel and reduces the laminar burning velocity, as discussed by Tromans [8]. Indeed, if this external strain is large enough, the flame can be extinguished. A recent paper by Abdel-Gayed and Bradley [66] summarises the criteria for flame extinction by a turbulent flow field. Again, when the flame kernel is small, it is more vulnerable to effects of the external strain fields. In engines, away from the misfire limits the convective effects, and near the misfire limits, the straining effects of the flow on flame developments are likely to be more important.

CAUSES OF CYCLIC VARIATIONS - During, the early phase, the flame surface area is small and flame propagation is highly dependent on the local turbulent flow field. Once the flame kernel diameter is larger than the length scales of the surrounding turbulent flow field, the flame front passes simultaneously through several turbulent eddies which affect it locally. These local fluctuations, are averaged out and flame development will depend on average turbulence parameters which can be expected not to vary from cycle to cycle. Hence, it is argued, cyclic variations cannot set in once the flame kernel is larger than a critical size (e.g. Refs. 6 and 8) and it has indeed been observed that cyclic variations originate during the initial stage of combustion (e.g. Refs. 3-5). Thus, it is generally accepted that the interaction of the turbulent flow field with the flame kernel during its development phase is the major cause of cyclic variations. There is a large body of

circumstantial evidence for this inference as discussed by Young [1] though direct and concrete evidence has been sparse mainly because of the difficulties in measuring in-cylinder flows. Recent work using Laser Doppler Anemometry and conditional analysis has demonstrated the direct correlation between flow velocity near the spark, near the time of spark breakdown, early flame development rate and pressure development [10, 65]. However, we must expect some cyclic variation in the local mixture strength near the spark and this is bound to contribute to cyclic variation in overall combustion (e.g. Ref. 67) if only because through its effect on laminar burning velocity, it will influence the interaction of the flame kernel with the turbulent flow field.

It follows from the above that the quicker the flame kernel reaches a critical size, the lower the cyclic variation [6, 8, 9, 60, 67].

EFFECT OF IGNITION ON EARLY FLAME DEVELOPMENT - It has been repeatedly demonstrated that enhanced ignition can increase early flame development rates (e.g. 12-14) and result in reduced cyclic variations (e.g. 58-61). The spark discharge process also has an important influence - near the misfire limits - on flame initiation. There are different views about the best approaches to optimise the spark discharge - in terms of energy, duration and nature - to yield the best results in terms of flame initiation and development. We discuss these approaches in the next section.

PRACTICAL APPROACHES TO IMPROVED SPARK IGNITION

It is useful to identify two separate areas to which improved ignition could contribute:

- (i) flame initiation which would be important in regimes where the engine is operating near the misfire limit and
- (ii) increase in early flame development rates and the consequent decrease in cyclic variations which could be important in the operating regimes sufficiently away from the misfire limit.

Any improved system must also satisfy the obvious practical constraints such as cost, reliability, ease of maintenance and lack of unacceptable side effects in terms of safety and interference with other electrical and electronic systems on the vehicle. The system must of course be capable of generating voltages high enough to ensure breakdown in all operating regimes; this is rarely a problem in modern ignition systems except on damp mornings when voltage can leak away from the leads instead of building up across the gap. The total electrical energy dissipated per spark event in a practical ignition system is between 30 and 100 mJ [27]. There are several points of view, some directly conflicting, as to the best strategy of delivering this in terms of the nature and duration of the spark. We discuss these approaches below and we will concentrate on the concepts rather than the engineering details. We are also not concerned with the many technical

improvements that have been achieved, especially through micro-electronics, such as in the management of spark timing.

THE ULTRA SHORT DURATION BREAKDOWN SPARK - Maly and co-workers [12, 27, 35, 56, 58] have argued that ignition systems should be redesigned so that most of the electrical energy is dissipated in the breakdown phase. They achieve this by discharging a pulse capacitor across the gap in tens of nanoseconds. This would ensure that energy is transferred to the gas most efficiently and produce sharp temperature gradients and the right plasma geometry to enhance the initial flame speed. Electrode erosion is also expected to be small. They argue that energy dissipated at later times as in the glow discharge in a coil ignition system, becomes increasingly irrelevant to flame propagation as the flame front moves away from the spark gap. They have demonstrated that such an ignition system leads to the improvement in the operation of a commercial engine in terms of reduced emissions, fuel consumption and engine roughness [58]. These improvements are especially noticeable near the lean operating limit.

SHORT DURATION CAPACITIVE IGNITION SYSTEMS - These are similar in principle to the breakdown ignition system discussed in the previous section in that the main energy storage device is a capacitor rather than the induction coil. The spark duration is still considerably shorter than in the conventional coil ignition system. It will result in an arc discharge rather than a glow discharge and hence will be more efficient at transferring energy to the gas though electrode erosion rates also will be very high. A recent commercial system along these lines was announced by Saab (e.g. Ref. 69). This system uses a larger plug gap - 1.5 mm - than is usual in order to increase the probability of ignition under limiting conditions and a separate, small coil for each plug. The author is not aware of any published material which demonstrates the improvement brought about by such an ignition system in engine operation; similar systems have been used on high performance two-stroke motor bikes.

REPETITIVE SPARKS - Kono et. al. have demonstrated [48] that a rapid succession of short duration sparks enhances the probability of ignition considerably in limiting conditions in flowing mixtures. They have also emphasised the need to have thin spark electrodes or electrodes with special configuration which produce low intensity turbulence in their wake. There does not appear to be a practical/commercial ignition system which incorporates these ideas.

LONG DURATION SPARKS - There is now growing evidence that extended spark duration improves engine stability under difficult operating conditions [57, 60, 61] Aiman [57] reported that extended spark duration (up to 7 ms for 30% dilution) improves engine operation at high exhaust gas recirculation rates. Nakai and co-workers (e.g. 60, 67) have demonstrated similarly that lengthening the spark duration (up to 7 ms) reduces the heat release delay and

markedly suppresses misfires near the lean limit, in an engine. They also conclude that any further lengthening of the spark causes fuel economy to deteriorate because of the increase in electric power consumption. A commercial ignition system apparently resulting from this work has been announced by Nissan [70] and is claimed to bring appreciable improvements in idling stability, acceleration and fuel economy.

IMPROVEMENTS IN SPARK PLUGS - It has been long appreciated [e.g. 1] that ignition further from the combustion chamber wall reduces cyclic variation-presumably through the geometric effects on flame surface area as discussed by Keck and co-workers [63, 64]. Spark plugs with extended electrodes would make it possible to move the point of ignition more towards the centre. Such plugs would also have high electrode temperatures which is also beneficial for ignition [71] though it considerably reduces plug life. Improvements in electrode materials allow extended electrodes to be used in practice. Again, the author is not aware of any systematic study of the effects of such modifications on engine or vehicle operation.

IMPROVEMENTS THROUGH 'SPARK-AIDER' FUEL ADDITIVES - Work within the Shell group of laboratories has shown that certain fuel additives - alkali and alkaline earth metal compounds collectively known as 'spark aiders' - significantly increase early flame development rates and reduce cyclic variation [72]. These additives act by depositing material - believed to be of low electron work function - on the electrodes. This in turn is believed to increase the efficiency with which the spark energy is transferred to the gas - mainly by reducing the cathode fall in the glow discharge phase and also by promoting the transition from glow to the arc phase during some part of the discharge. Thus the ignition process can be improved without any modification to the ignition system hardware. During the recent development of a commercial additive package incorporating the spark aider, extensive vehicle and field tests were carried out; of these, the cold weather dynamometer tests have been described in Ref. 73 and the consumer reaction type trials will be reported elsewhere. The tests show that the 'spark-aider' additive clearly brings about an improvement in driveability parameters such as idling performance and acceleration performance.

DISCUSSION - There are many approaches to improve spark ignition. Of these, the case for the breakdown mode appears to have been overstated by Maly and co-workers, though their arguments, in essence, are valid. For instance, it is known that optimum spark duration can be fairly long ($\sim 300 \mu s$) (e.g. Ref. 45) - thus energy dissipated long after breakdown, does contribute to ignition. Early flame development rates are also improved by the energy delivered after breakdown [14]. Recent theoretical work also suggests that a continuous long duration heat supply at the centre of the expanding flame kernel, as in the glow discharge phase of a conventional spark, assists flame initiation

[37-39]. The experience with spark aiders also suggests that energy dissipated after breakdown contributes to flame development [72]. More importantly, in a real engine, the charge is unlikely to be completely premixed under all conditions at the time of ignition. In such circumstances, if the discharge event were to last only a short time, there is a possibility that it will take place when the local mixture strength is outside the flammability limits and the engine will misfire badly - there is anecdotal evidence that this happens in some engines with ultra short duration sparks. This could be alleviated to an extent by using longer spark gaps or repetitive discharges.

There are other capacitive discharge systems which produce sparks of duration longer than the breakdown system but still much shorter than the conventional coil systems. This would perhaps be better for early flame development but still not very good for ignition probabilities. There are also many disadvantages associated with such systems. These include increases in radio interference; flashover and excessive leakage currents through the components; risk of injury because these systems need to work at higher voltages compared to an inductive system; electrode erosion. The breakdown spark system is believed not to suffer from this last handicap. However, it is not clear if this is indeed true because it is now known that cathode spots at which electrode material actually melts are always formed during breakdowns [21]. These handicaps can be overcome but at increased cost and complexity. Finally it is now well established that long duration sparks improve engine stability and operation under difficult operating conditions. On balance it appears that the best strategy is to increase the energy made available to the gas throughout the period of early flame growth - before the flame front has moved too far away from the spark channel. The lower the laminar burning velocity, the longer is this period. Thus under conditions when laminar burning velocity is low, such as with lean mixtures or with high exhaust gas recirculation, more of the energy in the longer duration spark can be expected to contribute directly to early flame development. The longer duration sparks also increase the probability of successful flame initiation near the limiting conditions. Similar effects can be achieved by using 'spark aider' fuel additives which are believed to lead to an increase in the efficiency with which energy is transferred after the breakdown phase, to the gas.

In terms of engine operation, it appears that the improvements in ignition are mostly noticeable near the lean limits. As discussed by Quader [71] it is difficult to determine whether engine stability near these limits is governed by failure to initiate the flame or by incomplete combustion due to slow flame propagation. Nakai et. al. [60] have also discussed this question and have shown that stability in at least some regimes like idling, can be improved by ensuring better flame initiation. Improved spark ignition

can be expected to contribute to improvements in both flame initiation and flame propagation through its affect on early flame development.

CONCLUSIONS

Cyclic variations in spark ignition engines can be reduced at source by reducing the variations in combustion. These arise during the early phase of flame development and can be reduced by increasing the flame growth rate during this period by improving the spark discharge process. Engine operation in regimes where flame initiation is difficult can also be improved through improvements in the spark discharge process. Amongst the various approaches suggested, perhaps the best strategy is to increase the energy made available to the gas throughout the period of early flame growth - while the flame front is still near enough to the spark discharge channel to be influenced by it. The lower the laminar burning velocity, the longer is this period. Thus under difficult conditions when laminar burning velocity is low, such as with lean mixtures and high exhaust gas recirculation the longer duration sparks can be expected to contribute directly to early flame development as well as to increased probability of flame initiation. Similar improvements in flame development and in engine operating parameters have been demonstrated, with 'spark aider' fuel additives without modifying the ignition system hardware. In general, improvements in spark ignition lead to noticeable improvements in engine operation near lean limit conditions. In terms of vehicle operation these improvements are in the 'driveability' criteria such as idling stability and part throttle acceleration performance. If and when engine design trends move towards lean burn and high exhaust gas recirculation concepts, such problems can be expected to become more pressing.

REFERENCES

1. Young, M.B., SAE Paper No. 810020, 1981.
2. Young, M.B., SAE Paper No. 800459, 1980.
3. Soltau, J.P., Proc. Inst. Mech. E., 2, p.99, 1960-61.
4. Peters, B.D. and Borman, G.L., SAE Paper No. 700064, 1970.
5. Arrigoni, V., Calvi, F., Cornetti, G.M. and Pozzi, U., SAE Paper No. 730088, 1973.
6. Winsor, R.E. and Patterson, D.J., SAE Paper No. 730086, 1973.
7. Barton, R.K., Lestz, S.S. and Meyer, W.E., SAE Paper No. 710163, 1971.
8. Tromans, P.S., Fluid Mechanics of Combustion systems, (Ed.s Morel, T., Lohman, R.P. and Rackley, J.M.) p.201, ASME Publications, 1982.
9. Kalghatgi, G.T., Combust. Flame, 60, p.299, 1985.
10. Swords, M.D., Kalghatgi, G.T. and Watts, A.J., SAE Paper No. 821220, 1982.
11. Vichievsky, R., Proceeding on the Joint Conference on Combustion, IME-ASME, 1955.

12. Maly, R. and Vogel, M., Seventeenth Symposium (International) on Combustion, p.821, Combustion Institute, 1979.
13. Desoete, G.G., International Conference on Combustion in Engineering, Vol. 1, p.93, I. Mech. E., 1983.
14. Malov, V.V., G.D. 85, Proceedings of the Eighth International Conference on Gas Discharges and their Applications, p. 507. Leeds University Press, 1985; also Anderson, R.W. and Lim, T.M., p.511.
15. Orrin, J.E., Vince, I.M. and Weinberg, F.J., Eighteenth Symposium (International) on Combustion, p.821, Combustion Institute, 1981.
16. Boston, P.M., Bradley, D., Lung, F.K.K., Vince, I.M. and Weinberg, F.J., Twentieth Symposium (International) on Combustion, Combustion Institute, p.141, 1985.
17. Dale, J.D. and Oppenheim, A.K., SAE Paper No. 810146, 1981.
18. Weinberg, F.J., International Conference on Combustion in Engineering, Vol. 93. I. Mech. E., 1983.
19. Smy, P.R. and Weinberg, F.J., GD 85, Proceedings of the Eighth International Conference on Gas Discharges and other Applications, pp.497-499, Leeds University Press, 1985.
20. Barreto, E., Reynolds, S.I. and Jurenka, H.J., J. App. Phys., 45, pp.3317-3327, 1974.
21. Barreto, E., Jurenka, H. and Reynolds, S.I., J. App. Phys., 48, p.4510, 1977.
22. Cobine, J.D., Gaseous Conductors - Theory and Engineering Applications, Dover Publications Inc., New York, 1958.
23. Lawton, J. and Weinberg, F.J. Electrical Aspects of Combustion, Oxford University Press, 1969.
24. von Engel, A., Ionized Gases, Clarendon Press, Oxford, 1965.
25. Loeb, L.B., Basic Processes of Gaseous Electronics, University of California Press, Berkeley, 1961.
26. Meek, J.M. and Craggs, J.D., (Editors) Electrical Breakdown of Gases, John Wiley and Sons Ltd., 1978.
27. Maly, R.R., "Spark ignition: Its physics and effect on the internal combustion engine" in Fuel Economy: Road Vehicles Powered by Spark Ignition Engines, Chapter 3, Ed.s: Hilliard, J.C. and Springer, G.S. Plenum Press, 1984.
28. Ziegler, G.W.F., Wagner, E.P. and Maly, R. Twentieth Symposium (International) on Combustion, Combustion Institute, p.1817, 1985.
29. Lewis, B. and von Elbe, G., Combustion, Flames and Explosion of Gases, Chapter 5, Academic Press, 1961.
30. Merzanov, A.G. and Averson, A.E., Combust. Flame, 16, p.89, 1971.
31. Dixon-Lewis, G. and Shepherd, I.G., Fifteenth Symposium, (International) on Combustion, p.1483, Combustion Institute, 1975.
32. Rosen, G., J. Chem. Phys. 30, p.298, 1959.
33. de Soete, G.G., Thirteenth Symposium (International) on Combustion, p.735, Combustion Institute, 1971.
34. Ballal, D.R. and Lefebvre, A.H., Fifteenth Symposium (International) on Combustion, p.1473, Combustion Institute, 1975.
35. Maly, R., Eighteenth Symposium (International) on Combustion, p.1747, Combustion Institute, 1981.
36. Akindele, O.O., Bradley, D., Mak, P.W. and McMahon, M., Combust. Flame, 47, p.129, 1982.
37. Deshaies, D. and Joulin, G., Combust. Sci. Tech., 37, p.99, 1984.
38. Joulin, G., Combust. Sci. Tech., 43, p.99, 1985.
39. Tromans, P.S. and Furzeland, R.M., Twentyfirst Symposium (International) on Combustion, Munich, 1986.
40. Zeldovich, Y.B., Barenblatt, G.I., Librovich, B.V. and Makhviladze, G.M., The Mathematical Theory of Combustion and Explosion, Consultants Bureau, Plenum Publishing Corporation, 1985.
41. Arnold, J.S. and Sherburne, R.K., Fourth Symposium (International) on Combustion p.139, Williams and Wilkins, 1953.
42. Olsen, H.L., Gayhart, E.L. and Edmonson, R.B., Fourth Symposium (International) on Combustion, p.144, Williams and Wilkins, 1953.
43. Rose, H.E. and Priede, T., Seventh Symposium (International) on Combustion, p.436, Butterworth, London, 1959.
44. Ballal, D.R. and Lefebvre, A.H., Proc. Roy. Soc. London A., 357, p.163, 1977.
45. Kono, M., Kumagai, S. and Sakai, T., Sixteenth Symposium (International) on Combustion, p.757, The Combustion Institute, 1977.
46. Tromans, P.S. and O'Connor, S.J., Progress in Astronautics and Aeronautics, Vol. 95, p.421, AIAA, 1985.
47. Ballal, D.R. and Lefebvre, A.H., Combust. Flame 24, p.99, 1975.
48. Kono, M., Hatori, K., Iinuma, K., Twentieth Symposium (International) on Combustion, Combustion Institute, p.133, 1985.
49. Llewellyn Jones, F., J. Inst. Elect. Eng., 96, p.305, 1949.
50. Llewellyn Jones, F., Brit. J. App. Phys., 1, p.60, 1950.
51. Kimura, I. and Kumagai, S., J. Phys. Soc. Japan, p.599, May 1956.
52. Hurtley, D., Automobile Engineer, p.96, March 1969, and p.148, April 1969.
53. Rose, H.E. and Priede, T., Seventh Symposium (International) on Combustion, p.454, Butterworth, London, 1959.
54. Swett, C.C., Jr. Sixth Symposium (Int.) on Combustion, p.523, Reinhold, New York, 1956.
55. Sivashinsky, G.I., Acta Astronautica, 3, p.889, 1976.

56. Ziegler, G.F.W., Maly, R.R. and Wagner, E.P., International Conference on Combustion in Engineering, vol.1, p.81 I. Mech. E., 1983.
57. Aiman, W.R., Combust. Sci. Tech., 15, p.129 1977.
58. Ziegler, G.F.W., Wagner, E.P., Saggau, B., Maly, R. and Herden, W., SAE Paper No. 840992, 1984.
59. Anderson, R.W. and Asik, J.R., SAE Paper No. 850076, 1985.
60. Nakai, M., Nakagawa, Y., Hamai, K and Sone, M., SAE Paper No. 850075, 1985.
61. Hancock, M.S., Buckingham, D.J and Belmont, M.R., SAE Paper No. 860321, 1986.
62. Abdel-Gayed, R.G., Bradley, D. and Lwakabamba, S.B., First Specialists Meeting (International) of the Combustion Institute, Bordeaux, p.95, July 1981.
63. Beretta, G.P., Rashidi, M. and Keck, J.C., Combust. Flame, 52, p.217, 1983.
64. Keck, J.C., Nineteenth Symposium (International) on Combustion, p.1451, Combustion Institute, 1983.
65. Cole, J.B. and Swords, M.D., SAE Paper No. 800043, 1980.
66. Abdel-Gayed, R.G. and Bradley, D., Combust. Flame, 62, p.61, 1985.
67. Hamai, K., Kawajiri, H., Ishizuka, T. and Nakai, M., Twenty-first Symposium (International) on Combustion, Munich 1986.
68. Rashidi, M., Combust. Flame, 42, p.111, 1981.
69. Brown, S., Autocar, p.18, 23 Jan. 1985.
70. Yamaguchi, J., Automotive Engineering, Vol. 92, No.11, p.89, Nov. 1984.
71. Quader, A.A., SAE Paper No. 760760, 1976.
72. Kalghatgi, G.T., To be published in Combust. Sci. Tech., 1986.
73. Blackmore, D.R., Graiff, L.B., Harrow, G.A., Jones, J.M., Kalghatgi, G.T. and Miles R., International Conference on Petroleum-Based Fuels and Automotive Applications, p.47 I. Mech. E., London, 1986.