SNS COLLEGE OF TECHNOLOGY
(An Autonomous Institution)
COIMBATORE-35
DEPARTMENT OF MECHATRONICS ENGINEERING

BASICS OF COMBUSTION

The process of combustion in spark and compression ignition engines is best considered for petrol and diesel engines in turn. The knowledge of the more practical aspects of combustion has been gained after years of research and is by no means complete even now. For a complete picture of the factors involved, further reference should be made to appropriate sources. However, the combustion section here will give enough details to allow considered opinion about the design and operation of electronic fuel control systems.

Spark ignition engine combustion process

A simplified description of the combustion process within the cylinder of a spark ignition engine is as follows. A single high intensity spark of high temperature passes between the electrodes of the spark plug leaving behind it a thin thread of flame. From this thin thread combustion spreads to the envelope of mixture immediately surrounding it at a rate that depends mainly on the flame front temperature, but also, to a lesser degree, on the temperature and density of the surrounding envelope.

In this way, a bubble of flame is built up that spreads radially outwards until the whole mass of mixture is burning. The bubble contains the highly heated products of combustion, while ahead of it, and being compressed by it, is the still unburnt mixture.

If the cylinder contents were at rest this bubble would be unbroken, but with the air turbulence normally present within the cylinder, the filament of flame is broken up into a ragged front, which increases its area and greatly increases the speed of advance. While the rate of advance depends on the degree of turbulence, the direction is little affected, unless some definite swirl is imposed on the system. The combustion can be considered in two stages.

1. Growth of a self-propagating flame.
2. Spread through the combustion chamber.

The first process is chemical and depends on the nature of the fuel, the temperature and pressure at the time and the speed at which the fuel will oxidize or burn. Shown in Figure 1, it appears as the interval from the spark (A) to the time when an increase in pressure due to combustion can first be detected (B).

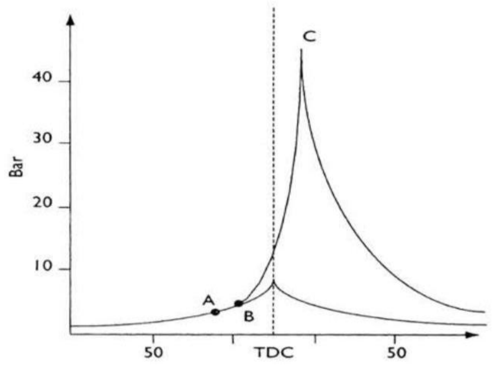

Figure 1. The speed at which fuel will oxidize or burn

This ignition delay period can be clearly demonstrated. if fuel is burned at constant volume, having been compressed to a self-ignition temperature, the pressure—time relationship is as shown in Figure 2.

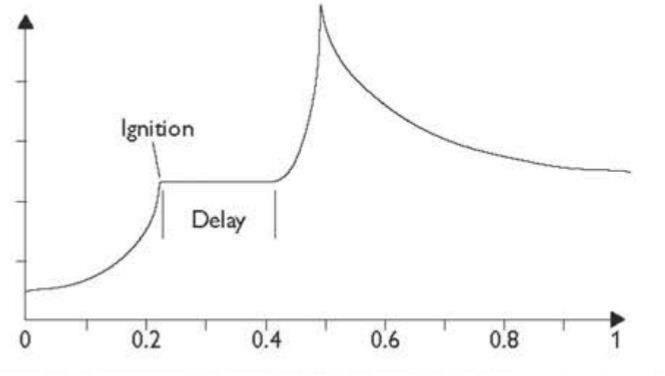

Figure 2. Fuel is burned at a constant volume having been compressed to a self-ignition temperature. The pressure-time relationship is shown

The time interval occurs with all fuels but may be reduced with an increase of compression temperature. A similar result can be demonstrated, enabling the effect ofmixture strength on ignition delay to be investigated

Referring to Figure 1, with the combustion under way, the pressure rises within the engine cylinder from (B) to (C), very rapidly approaching the 'constant volume' processof the four-stroke cycle. While (C) represents the peak cylinder pressure and the completion of flame travel, all available heat has not been liberated due to re- association, and what can be referred to as after-burning continues throughout the expansion stroke.

Range and rate of burning

The range and rate of burning issue can be summarised by reference to the followinggraphs:

Figure 3 shows the approximate relation between flame temperature and the time fromspark to propagation of flame for a hydrocarbon fuel.

Figure 4 shows the relation between the flame temperature and the mixture strength.Figure 5 shows the relationship between mixture strength and rate of burning.
These graphs show that the minimum delay time (A to B) is about 0.2 ms seconds withthe mixture slightly rich. While the second stage (B to C) is roughly dependent upon the degree of the turbulence (and on the engine speed) the initial delay necessitatesignition advance as the engine speed increases.

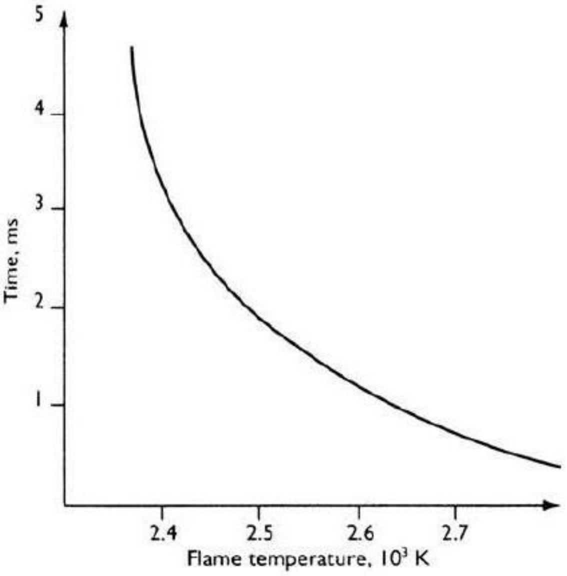

Figure 3. Approximated relationship between flame temperature and the time from spark to propagation of flame for a hydrocarbon fuel

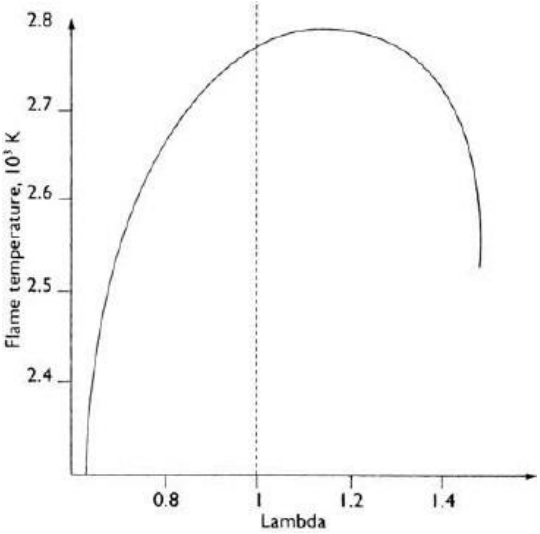

Figure 4. Relationship between flame temperature and mixture strength

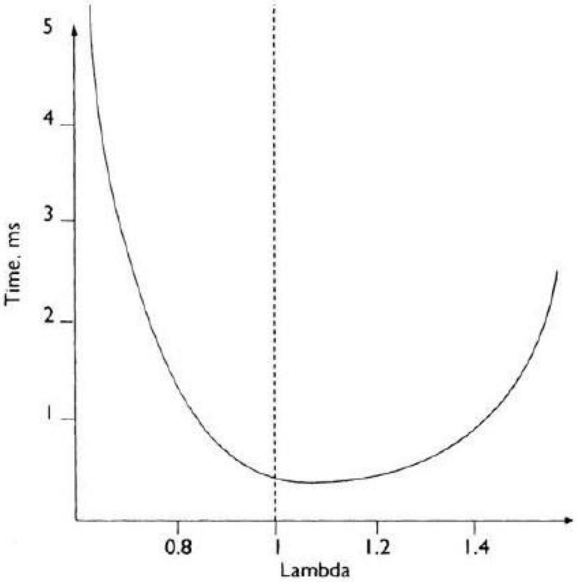

Figure 5. Relationship between mixture strength and rate of burning

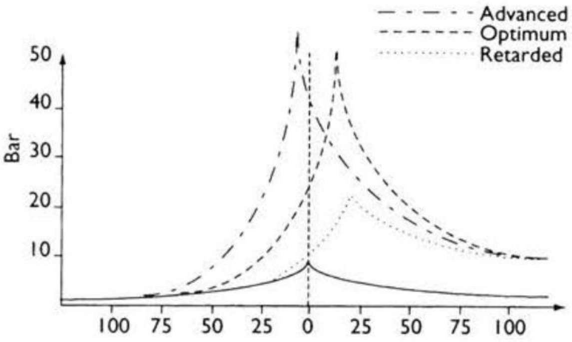

Figure 6. Effects of incorrect ignition timingon fuel burn

Figure 6 shows the effects of incorrect ignition timing. As the ignition is advanced thereis an increase in firing pressure or maximum cylinder pressure, generally accompaniedby a reduction in exhaust temperature. The effect of increasing the range of the mixture strength speeds the whole process up and thus increases the tendency to detonate.

Detonation

The detonation phenomenon is the limiting factor on the output and efficiency of thespark ignition engine. The mechanism of detonation is the setting up within the enginecylinder of a pressure wave travelling at such velocity as, by its impact against the cylinder walls, to set them in vibration, and thus produce a high pitched ‘ping’. Whenthe spark ignites a combustible mixture of the fuel and air, a small nucleus of flame builds up, slowly at first but accelerating rapidly. As the flame front advances it compresses the remaining unburned mixture ahead of it. The temperature of the unburned mixture is raised by compression and radiation from the advancing flame until the remaining charge ignites spontaneously. The detonation pressure wave passes through the burning mixture at a very high velocity and the cylinder walls emitthe ringing knock.

Detonation is not too dangerous in small engines because it is usually avoided at thefirst warning by easing the load, but at higher speeds, where the noise level is high, the characteristic noise can and often does go undetected. It can be extremely dangerous, prompting pre-ignition and possibly the complete destruction of the engine.

High compression temperature and pressure tend to promote detonation. In addition,the ability of the unburnt mixture to absorb or get rid of the heat radiated to it by theadvancing flame front is also important. The latent enthalpy of the mixture and the design of the combustion chamber affect this ability. The latter must be arranged foradequate cooling of the unburnt mixture by placing it near a well-cooled feature suchas an inlet valve.

The length of flame travel should be kept as short as possible by careful positioning ofthe point of ignition. Other factors include the time (hence the ignition timing), sincethe reaction in the unburnt mixture must take some time to develop; the degree of turbulence (in general, higher turbulence tends to reduce detonation effects); and, most importantly, the tendency of the fuel itself to detonate.

Some fuels behave better in this respect. Fuel can be treated by additives (e.g. tetra-ethyl lead) to improve performance. However, this aggravates an already difficult pollution problem. A fuel with good anti-knock properties is iso-octane, and a fuel thatis susceptible to detonation is normal heptane.

To obtain the octane number or the anti-knock ratings of a particular blend of fuel, atest is carried out on an engine run under carefully monitored conditions, and the onsetof detonation is compared with those values obtained from various mixtures of iso- octane and normal heptane. If the performance of the fuel is identical to, for example,a mixture of 90% iso-octane and 10% heptane, then the fuel is said to have an octanerating of 90.

Mixing water, or methanol and water, with the fuel can reduce detonation. A mainly alcohol-based fuel, which enables the water to be held in solution, is also helpful so that better use can be made of the latent enthalpy of the water

Pre-ignition

Evidence of the presence of pre-ignition is not so apparent at the onset as detonation,but the results are far more serious. There is no characteristic ‘ping’. In fact, if audibleat all, it appears as a dull thud. Since it is not immediately noticeable, its effects are often allowed to take a serious toll on the engine. The process of combustion is not affected to any extent, but a serious factor is that control of ignition timing can be lost.

Pre-ignition can occur at the time of the spark with no visible effect. More seriously, the ‘auto-ignition’ may creep earlier in the cycle. The danger of pre-ignition lies not so much in development of high pressures but in the very great increase in heat flow tothe piston and cylinder walls. The maximum pressure does not, in fact, increase appreciably although it may occur a little early.

In a single-cylinder engine, the process is not dangerous since the reduction usually causes the engine to stall. In a multiple-cylinder engine the remaining cylinders (if onlyone is initially affected), will carry on at full power and speed, dragging the pre-ignitingcylinder after them. The intense heat flow in the affected cylinder can result in pistonseizure followed by the breaking up of the piston with catastrophic results to the wholeengine.

Pre-ignition is often initiated by some form of hot spot, perhaps red-hot carbon or somepoorly cooled feature of combustion space. In some cases, if the incorrect spark plugis used, over-heated electrodes are responsible, but often detonation is the prime cause. The detonation wave scours the cylinder walls of residual gases present in a film on the surface with the result that the prime source of resistance to heat flow is removed and a great release of heat occurs. Any weaknesses in the cooling system are tested and any hot spots formed quickly give rise to pre-ignition.

Combustion chamber

To avoid the onset of detonation and pre-ignition, a careful layout of the valves and spark plugs is essential. Smaller engines, for automotive use, are firmly tied to the poppet valve. This, together with the restriction of space involved with high compression ratios, presents the designer with interesting problems.

The combustion chamber should be designed bearing in mind the following factors:

- The compression ratio should be 9: 1 for normal use, 11 or 12: 1 for higher performance.

- The plug or plugs should be placed to minimize the length of flame travel. They should not be in pockets or otherwise shrouded since this reduces effective cooling and also increases the tendency toward cyclical variations.

Experimental evidence shows a considerable variation in pressure during successive expansion stokes. This variation increases, as the mixture becomes too weak or too rich. Lighter loads and lower compression ratios also aggravate the process. While thesize and position of the point of maxi-mum pressure changes, the mean effective pressure and engine output is largely unaffected.

Stratification of cylinder charge

A very weak mixture is difficult to ignite but has great potential for reducing emissionsand improving economy. One technique to get around the problem of igniting weak mixtures is stratification.

It is found that if the mixture strength is increased near the plug and weakened in themain combustion chamber an overall reduction in mixture strength results, but with acorresponding increase in thermal efficiency. To achieve this, petrol injection is used – stratification being very difficult with a conventional carburation system. A system that uses this technique is gasoline direct injection, which can allow a petrol engine torun with much weaker air-to-fuel ratios.

Mixture strength and performance

The effect of varying the mixture strength while maintaining the throttle position, engine speed and ignition timing constant is shown in Figure 7.

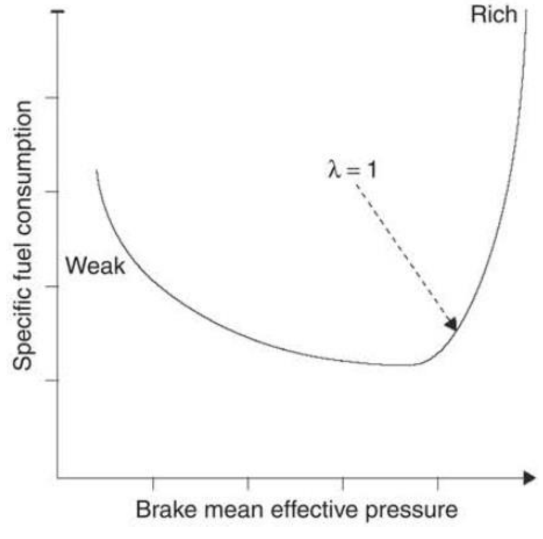

Figure 7. Effect of varying mixture strength while keeping throttle position, engine speed and ignition timing constant

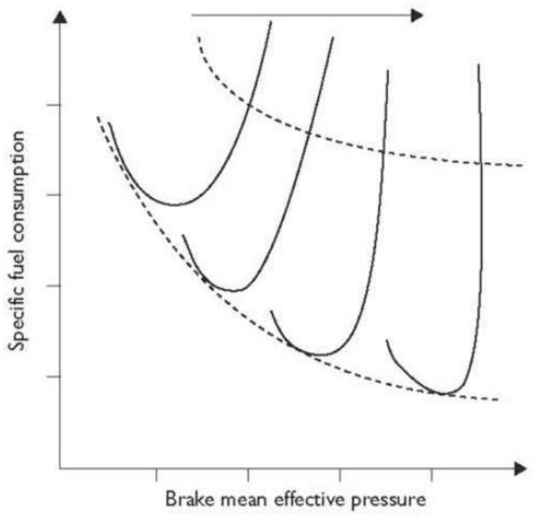

Figure 8. Effect operating at part throttle with varying mixture strength

Figure 8 shows the effect of operating at part throttle with varying mixture strength. The chemically correct mixture of approximately 14.7: 1 lies between the ratio that provides maximum power (12: 1), and minimum consumption (16: 1). The stoichiometric ratio of 14.7: 1 is known as a lambda value of one. Figure 9 compares engine power output and fuel consumption with changes in air—fuel ratio.

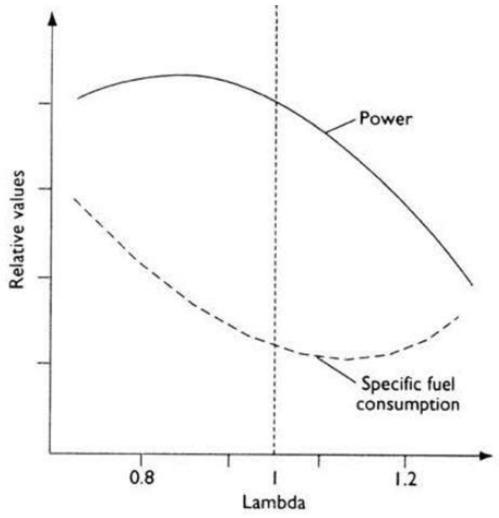

Figure 9. Comparison of engine power output and fuel consumption with changes in air-fuel ratio

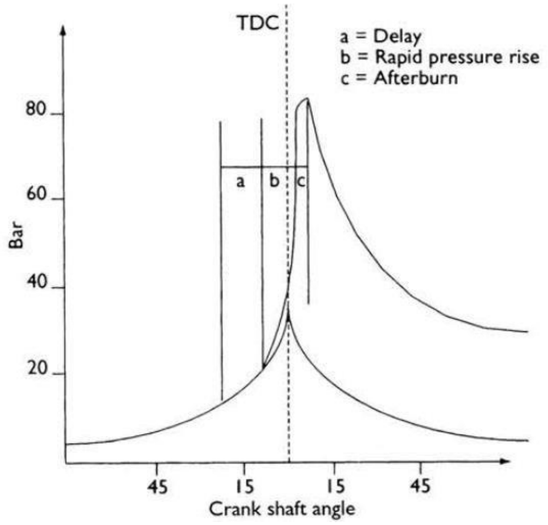

Figure 10. Phases of diesel combustion timing constant

Compression ignition (CI) engines

The process of combustion in the compression ignition engine differs from that in a spark ignition engine. In this case the fuel is injected in a liquid state, into a highly compressed, high-temperature air supply in the engine cylinder. Each minute dropletis quickly surrounded by an envelope of its own vapour as it enters the highly heatedair. This vapour, after a certain time, becomes inflamed on the surface. A cross-sectionof any one droplet would reveal a central core of liquid, a thin surrounding film of vapour, with an outer layer of flame. This sequence of vaporization and burning persists as long as combustion continues.

The process of combustion (oxidization of the hydrocarbon fuel), is in itself a lengthyprocess, but one that may be accelerated artificially by providing the most suitable conditions. The oxidization of the fuel will proceed in air at normal atmospheric temperatures, but it will be greatly accelerated if the temperature is raised. It will takeyears at 20 °C, a few days at 200 °C and just a few minutes at 250 °C. In these cases,the rate of temperature rise due to oxidization is less than the rate at which the heat isbeing lost due to convection and radiation. Ultimately, as the temperature is raised, a critical stage is reached where heat is being generated by oxidization at a greater ratethan it is being dissipated.

The temperature then proceeds to rise automatically. This, in turn, speeds up the oxidization process and with it the release of heat. Events now take place very rapidly;a flame is established and ignition takes place. The temperature at which this criticalchange takes place is usually termed the self-ignition temperature of the fuel. This, however, depends on many factors such as pressure, time and the ability to transmitheat from the initial oxidization.

At a temperature well above the ignition point, the extreme outer surface of the droplet immediately starts to evaporate, surrounding the core with a thin film of vapour. Thisinvolves a supply of heat from the air surrounding the droplet in order to supply the latent enthalpy of evaporation. This supply is maintained by continuing to draw on themain supply of heat from the mass of hot air,

Ignition can and will occur on the vapour envelope even with the core of the droplet still liquid and relatively cold. Once the flame is established, the combustion proceedsat a more rapid rate. This causes a delay period, after injection commences and beforeignition takes place. The delay period therefore depends on:

- Excess of air temperature over and above the self-ignition temperature of thefuel.
- Air pressure, both from the point of view of the supply of oxygen and improvedheat transfer between the hot air and cold fuel.

Once the delay period is over, the rate at which each flaming droplet can find fresh oxygen to replenish its consumption controls the rate of further burning. The relativevelocity of the droplet to the surrounding air is thus of considerable importance. In thecompression ignition engine, the fuel is injected over a period of perhaps 40-500 of crank angle. This means that the oxygen supply is absorbed by the fuel first injected,with a possible starvation of the last fuel injected.

This necessitates a degree of turbulence of the air so that the burnt gases are scavenged from the injector zone and fresh air is brought into contact with the fuel. Itis clear that the turbulence should be orderly and not disorganized, as in a spark ignition engine, where it is only necessary in order to break up the flame front.

In a compression ignition engine the combustion can be regarded as occurring in threedistinct phases as shown in Figure 10

- Delay period
- Rapid pressure rise.
- After-burning, i.e. the fuel is burning as it leaves the injector.

The longer the delay, the greater and more rapid the pressure rise since more fuel willbe present in the cylinder before the rate of burning comes under direct control of therate of injection. The aim should be to reduce the delay as much as possible, both forthe sake of smooth running, the avoidance of knock and also to maintain control overthe pressure change. There is, however, a lower limit to the delay since, without delay,all the droplets would burn as they leave the nozzle. This would make it almost impossible to provide enough combustion air within the concentrated spray and the delay period also has its use in providing time for the proper distribution of the fuel. The delay period therefore depends on:

- The pressure and temperature of the air.
- The cetane rating of the fuel.
- The volatility and latent enthalpy of the fuel.
- The droplet size.
- Controlled turbulence.

The effect of droplet size is important, as the rate of droplet burning depends primarilyon the rate at which oxygen becomes available. It is, however, vital for the droplet topenetrate some distance from the nozzle around which burning will later become concentrated. To do this, the size of the droplets must be large enough to obtain sufficient momentum at injection. On the other hand, the smaller the droplet the greater the relative surface area exposed and the shorter the delay period. A compromise between these two effects is clearly necessary.

With high compression ratios (15: 1 and above) the temperature and pressure are raised so that the delay is reduced, which is an advantage. However, high compressionratios are a disadvantage mechanically and also inhibit the design of the combustion chamber, particularly in small engines where the bumping clearance consumes a largeproportion of the clearance volume.

Combustion chamber design – diesel engine

The combustion chamber must be designed to:

- Give the necessary compression ratio.
- Provide the necessary turbulence.
- Position for correct and optimum operation of the valves and injector.

These criteria have effects that are interrelated. Turbulence is normally obtained at theexpense of volumetric efficiency. Masked inlet valves (which are mechanically undesirable) or ‘tangent’ directional ports restrict the air flow and therefore are restrictive to high-speed engines.

To assist in breathing, four or even six valves per cylinder can be used. This arrangement has the advantage of keeping the injector central, a desirable aim for direct injection engines. Large valves and their associated high lift, in addition to providing mechanical problems often require heavy piston recesses, which disturb squish and orderly movement of the air.

A hemispherical combustion chamber assists with the area available for valves, at theexpense of using an offset injector. Pre-combustion chambers, whether of the air cellor ‘combustion swirl’ type have the general disadvantage of being prone to metallurgical failure or at least are under some stress since, as they are required to produce a ‘hot spot’ to assist combustion, the temperature stresses in this region areextremely high. There is no unique solution and the resulting combustion chamber isalways a compromise.