Chapter 1.

Flame Initiation, Propagation and Combustion.

It may seem obvious but let us start by observing that the purpose of an engine is to convert chemical energy in the fuel into mechanical energy to then emerge as rotational force at the output shaft. There is an intermediate stage where the chemical energy is converted into heat energy and that is the function of the combustion process.

Burning the fuel raises the temperature and pressure of a body of gas which is then allowed to expand, in the course of which a proportion of the heat energy from the fuel is converted into work. Everything depends upon the combustion process, which the entire engine is designed to feed, control and exploit. It therefore makes a good place to start in a quest to understand the technology of engines.

The above two paragraphs could apply to various types of engine; diesel, gas turbine, two stroke, to name a few, but from here on the text will mainly be confined to the spark ignition, reciprocating piston petrol engine, broadly operating according to the Otto cycle, that powers the vast majority of motor cars and racing cars.

Most people will be familiar with Otto's basic four stroke cycle of: induction, compression, combustion/expansion, exhaust, - or more flippantly: suck, squeeze, bang, puff. Rolls-Royce's Sir Stanley Hooker once quipped that 'a four stroke engine had one stroke to produce power and three to wear it out' which is perhaps a light-hearted observation from someone who had contributed so much to the success of the legendary Merlin V12.

In the very early days of engine development there was a general belief that all that was needed was to apply a spark anywhere to the charge and it would all go 'bang' and explode to propel the piston down the cylinder, rather like a bullet down a gun barrel. This soon gave way to the acceptance that combustion was actually a more useful process if the charge was steadily consumed by the flame spreading through it after initiation by the spark.

Like so many things in this world, the flame of combustion within an engine needs to be nurtured through its early existence, encouraged to develop, allowed to burst into full bloom, then the remains disposed of after fulfillment.

Already it can be seen that combustion is not such a simple matter after all. Let us now look into the subject more thoroughly.

Combustion Basics.

We will assume that by whatever means a fuel/air charge has been introduced to the cylinder. It is self evident that the mixture is compressed by the rising piston and ignited by the spark plug but the actual mechanism of combustion is very complex. The one thing it is not meant to be is an explosion. It should be a rapid but not instantaneous process, whereby the charge is consumed in a steady controlled manner.

Hydrocarbon fuels such as petrol (gasoline) oxidise whenever they are exposed to oxygen, but in simple exposure to air at room temperature the process is so slow as to be insignificant. The rate of oxidation speeds up with increasing temperature and takes place regardless of the ratio of fuel to air until eventually one or the other is totally consumed (assuming agitation or other means of bringing uncombined molecules of fuel and air together). As the reaction is exothermic (it generates heat) the oxidation of any one molecule of fuel gives off heat which may be available to speed up the oxidation of its neighbour, which can perform a similar service for the next, and so on. The likelihood of this chain of events accelerating fast enough to cause what is recognised as flaming combustion is influenced by several factors:

1. The rate of heat release must be greater than that at which it is dissipated amongst the surroundings.

2. Neighbouring molecules must be intimate enough to receive significant heat.

3. Oxygen and fuel molecules must be sufficiently intimate for reaction to occur.

4. The proportions of fuel and air should be near optimum otherwise some of the heat available will be absorbed, and therefore wasted, by surplus molecules which will have no partners with which to react.

5. Time is an important factor because the reactions are not instantaneous and the ability of the fuel to vaporise, in preparation for combustion, during the compression process, will vary with speed and throttling.

Clearly the variables of temperature, pressure, air/fuel ratio, mixture quality and exposure time, must all be in some sort of balance for any fuel/air mixture to be able to support combustion. This does not mean that no reactions occur unless these factors are in more or less the right proportions, just that self-propagating, flaming combustion will only take place if certain conditions are satisfied, yet a deficiency of one factor can often be compensated by an increase of another. An example is that for a weak mixture more time is likely to be needed for combustion to take place (perversely, a rich mixture does not slow down nearly as much).

Alternatively, an increase of compression ratio will speed the process up. Similarly, as compression pressure rises so the extremes of weak and rich mixture which can be tolerated are extended. A large spark gap, needing more voltage to strike the arc, introduces more energy thereby aiding ignition of weaker mixtures, although there is more to this as we shall see. Increasing the intake air temperature and/or improving fuel atomisation will extend the rich/weak mixture tolerance, although the former will also make a malady called detonation (see Chapter 5) more likely to occur when operating under high load conditions. Less obviously, low pressures in throttled operation during idling and light load upset exhaust scavenging so a high proportion of exhaust gas remains to dilute the new charge, absorbing combustion heat and getting in the way of molecules which might otherwise react. To aid stable running it used to be usual to have a slightly richer mixture in these circumstances so that some fuel will always find the available oxygen.

Of course in a spark ignition petrol engine the compression pressure is not sufficient to initiate combustion but it does increase the reactivity of the whole fuel/air charge. The spark then provides the energy to raise the temperature of a small part of the charge to a level at which heat is generated faster than it can be dissipated, causing a chain reaction as described above and resulting in a flame becoming established.

Organised Combustion.

Early thinking produced the rather naive idea that the ideal combustion chamber would be a sphere with the ignition point at the centre, having equal flame travel in all directions, which of course is impractical.

However, a hemispherical shape can be practical and by placing the ignition point in the centre of the diametric flat side, the ideal of equal flame travel can be achieved. The requirement for inlet and exhaust valves makes this sort of shape difficult to produce although there was one notable example (Rover P3) which will be described later. Eventually it became obvious that the charge is unlikely ever to be static, nor is it desirable for it to be, so the idea of a flame smoothly radiating out from the spark plug does not represent what happens in a real engine. Deliberately induced charge movement is recognized as the most effective way of promoting efficient combustion but there are subtleties in the process that cannot be ignored. Chapter 2 delves into methods by which charge movement and turbulence can be induced by the design of the engine.

At this point it is worth digressing to note that there is a fundamental difference between the way combustion is developed in the spark ignition engine compared to the diesel, quite apart from the different method of ignition and the way the fuel is introduced. The diesel compresses air alone to a very high pressure and temperature so that when the fuel is introduced there will be reactions that quickly develop into combustion. The fuel droplets first begin to evaporate which initially absorbs heat, then the resulting vapour begins to oxidise in an exothermic reaction. The heat released thereby speeds up the similar reactivity of any adjacent fuel droplets, leading to a rapid increase in the rate of the process until what we know as flaming combustion develops. It is important to the process that the fuel droplets must be moving relative to the air so that combustion products are swept away enabling fresh evaporating vapour to be ignited, requiring a continuous but controlled movement of air across the fuel spray (Fig. 1.1).

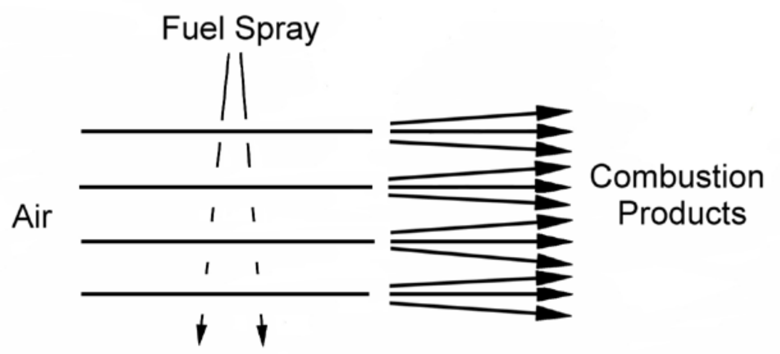

Fig. 1.1 Diesel combustion.

The rate at which fuel is injected determines the rate of pressure rise, approximating to combustion at constant pressure as the piston begins to descend. As each fuel droplet shrinks it eventually loses momentum and no longer burns to completion so the final result is a minute sooty particle impregnated with various carbonaceous compounds. Because of the difficulty of introducing fuel to all of the air charge, diesels generally operate with a small proportion of excess air at full rated power to maintain a clean, smoke free, exhaust. Pursuit of maximum power by using all the available air usually brings the penalty of excessive visible exhaust smoke. Deterioration of the injector spray pattern due to deposit fouling will also reduce the efficiency of the process causing the familiar smoky exhaust that old or neglected diesels often produce.

Diesel exhaust particles were recognized as hazardous to health if inhaled and were a serious obstacle to the diesel remaining acceptable as a motive power unit. This book is not about diesel engines but the way in which the particulate problem was solved is so interesting it is worthy of some space. A brief account is therefore added at the end of Chapter 4.

The conventional spark ignition engine is very different. Until recently it was standard practice for the fuel to be premixed with the air, entering the cylinder as a homogeneous, vapourising, combustible mixture. There is therefore no need to make the fuel seek the air because it will already be intimate with it. The spark initiates combustion at one point only (mostly) and it is necessary to allow the flame to develop and then spread around to consume the entire charge. This requires the charge movement to progress from early controlled motion into later random turbulence (Fig. 1.2).

According to classic theory the flame should be initiated by the spark in relatively tranquil conditions to first become established. It should then be encouraged to propagate steadily into the adjacent mixture, finally breaking up into a turbulent motion to spread the flame around and consume the entire charge. The terms ‘nurture’, ‘encourage’ and ‘burst into full bloom’ used in the opening section are indeed appropriate.

As combustion proceeds the temperature and pressure both rise and the pressure behind the flame front drives it onwards even faster. The reactivity of the remaining charge ahead of the flame is raised by the heat and extra compression it is now exposed to, so all these factors cause the process to gather speed. In practice, even if there were no charge motion the flame would advance in fits and starts because the mixture quality is never perfect and the flame speed will vary accordingly but turbulent motion will help to spread the flame around to consume the entire charge.

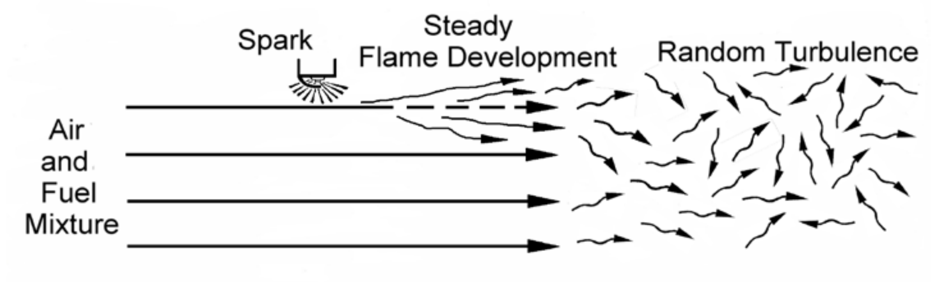

Fig. 1.2 Conventional spark ignition combustion.

Too little turbulence and the burn rate may be too slow requiring more ignition advance, but too much turbulence too soon can also be harmful. Some of the Formula 1 turbo engines of the eighties suffered from slow burning at very high boost pressures, the reverse of what might be expected. One might surmise that the huge quantities of fuel and air forced into the cylinders, creating extremely violent turbulence and taking heat away from the flame too quickly, was to some extent the cause. Once fuels with special burn characteristics began to be developed, power outputs rose dramatically. It is unlikely that any normal engine would ever suffer from too much turbulence, although quite a few might suffer from lack of it in the low to moderate speed / part throttle regime.

Slow combustion at full power is undesirable, partly because the pressure losses and loads on the structure are more prolonged and also because detonation (described in Chapter 5) is more likely to occur. The expanding flame must therefore be swept through the whole charge sufficiently quickly before there is a chance for spontaneous ignition to be provoked in the extremities. On the other hand if combustion is too fast the sharper rate of pressure rise also places higher loads on the structure and increases torsional stab loads on the crankshaft so the engine may then be criticised for "roughness".

Finally the rate of combustion loses momentum and slows down due to the cooling effect of the chamber surfaces and the diminishing amount of unburnt mixture that is remaining.

13 pages follow.