PRE-IGNITION AND DETONATION

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Some time during 1916, with the Great War raging, English engine pioneer Harry Ricardo discerned the difference between detonation and pre-ignition. Today, almost 90 years later, people are still confusing the two, even though they are completely separate and distinct phenomena.

Pre-ignition

Pre-ignition is just what it says it is - ignition of the charge before the ignition spark. This takes place when there is some object in the combustion chamber hot enough to act as an ignition source. Typical examples are the glowing electrodes of a spark plug whose heat range is too hot for the application, or the incandescent head of an exhaust valve that is running hot for any reason, or the easily heated thin, sharp edge of some machined part.

When pre-ignition begins, just a few engine revolutions are needed to produce complete failure, and the visible result is that the center of the piston dome is collapsed to form a ragged hole from combustion chamber to crankcase. Usually the hot object ignites the charge very early, with the piston just beginning the compression stroke. The process of compressing (the) burning charge heats the piston with extreme rapidity. Naturally it is the part of the piston farthest from any cooling effect - the exact center - whose temperature rises fastest. Very shortly its temperature transforms it into pudding and the piston dome is pushed and broken downward.

Much complete nonsense has been uttered about pistons damaged in this way - for example that "The piston is getting too hot because the spark plug is too close to it." More than one inexperienced manufacturer has therefore produced cylinder heads which withdraw the spark plug up into a high recess, as far as possible from the piston - with no useful result.

Detonation

Detonation is an abnormal and destructive form of combustion, so first I will review what normal combustion is. When the spark passes across the plug electrodes, whatever is within the gap is heated to high temperature by the electric arc. This high temperature breaks apart molecules, allowing them to re-combine in new arrangements of lower energy. The energy difference is released as heat - the kinetic energy of the product molecules. The released heat in turn heats more fuel-air mixture to its ignition point, and the flame proceeds by this process.

If a chemically correct fuel-air mixture is prepared in a tube and is then ignited at one end, the flame front moves down the tube at a few inches per second - a distinctly leisurely speed. If this were the fastest that combustion flame could move, the internal combustion engine would never have come into being.

In an engine cylinder, pressure-time studies have revealed that combustion typically lasts about as long ATDC as it is ignited BTDC, so in an R-4360 radial of 5.75" bore, operating at 2700 rpm and 20 degrees BTDC ignition timing, the roughly 40 degree combustion period takes about 0.0025 second. If the plug were in the center of the combustion chamber (there are two, and they are located near the sides), that would imply a flame speed of almost 100 feet per second. How do we get from the quiescent mixture flame speed of a few inches per second to 100 feet per second? The answer is mixture turbulence. The piston's area is about 5.6 times greater than the area of the intake port, so at a mean piston speed of 2,700 feet per minute, the mean intake velocity is roughly 250 feet per second. That 170 mile-per-hour wind, rushing into the cylinder on the intake stroke, creates a big disturbance that doesn't dissipate much during compression. It turns into vigorous turbulence that is the real source of combustion flame speed. The kernel of flame created at the spark plug electrodes is swept away, shredded, and mixed into this tornado and is carried by it to all parts of the combustion chamber very promptly. It is no accident that the apparent flame speed (derived from our simplistic calculation), and the intake velocity, are of the same order of magnitude. The one is the creation of the other.

Combustion does not therefore take place along orderly flame fronts that march through the fuel-air mixture like armies. Instead the flame is folded, twisted, and shredded by turbulence so that even at its natural local speed of a few inches per second, the area aflame is so large it is able to consume the chamber contents as if a single flame front were moving at a steady 100 fps. In less turbulent combustion chambers, flame speed is slower, and in more turbulent ones, it can be faster. Combustion at 100 fps is not an explosion. It is not even close, for the reaction speed in explosions is of the order of thousands of feet per seconds. It is entirely wrong and misleading ever to refer to IC engine combustion as an explosion.

Now let's follow a bit of fuel-air charge on its way into the engine. Compression in the supercharger raises mixture temperature quite a bit, followed by further compression inside the engine cylinder. This takes us to several hundred degrees F, and now the sparks ignites the mixture. Two turbulent balls of flame whirl and expand from the spark plugs - compressing the unburned mixture ahead of them even more. No flame has yet reached our little bit of mixture, but its temperature is very high now as a result of the three compressions - one in the blower, one in the cylinder, and now further compression as combustion proceeds.

Here it is necessary to lay to rest another widely believed piece of nonsense - the one about detonation being the result of "colliding flame fronts". It's quite obvious that in any combustion chamber containing more than one operating spark plug, flame fronts will always intersect each other. Nothing of importance happens as a result - this is just part of normal combustion.

The temperature of a gas is a measure of the average energy of the molecules within it, but molecular velocity is a statistical matter, with some molecules moving faster and some slower than the mean. As the fuel-air mixture temperature rises, the energy of the most energetic molecules approaches a level at which their collisions with other molecules are violent enough to detach hydrogen atoms from fuel and to break paired oxygen atoms in the air. Such partial molecular breakdown signals the onset of what are called pre-flame reactions, and these have been the subject of much study.

As the flame front expands toward our bit of mixture, compression heats that mixture enough to generate an expanding variety of pre-flame reactions - reactions that are taking place before the flame front has come near. A variety of molecular fragments are not produced, such as OH-. Many of these are at first fleeting, coming into existence and then recombining back to what they were, but as the temperature rises the speed of fragment formation rises and so do the populations of molecular fragments. Now a strange thing happens. The nature of our bit of fuel-air mixture changes from being a substance that supports combustion as does a log in a fireplace, into a new and very sensitive material that is essentially an explosive.
Meanwhile, the swirling, expanding ball of flame is coming closer, and in our bit of unburned mixture, out somewhere near the wall of the combustion chamber, the population of highly reactive molecular fragments is increasing with every compression-driven rise in its temperature.

If the flame arrives first, our bit of mixture is ignited and burns up normally, at the prevailing "flame speed" which is actually the local velocity of some turbulent eddy. In this case there is no detonation, for the flame has consumed the mixture and all is well. The desirable feature of normal, so-called deflagrating combustion is that the heat energy is released in a controlled, relatively non-violent way. Ricardo observes in his book 'The High-Speed Internal Combustion Engine' that rates of pressure rise faster than about 40-psi per crank degree produce perceptible engine roughness and vibration. Engineers take care to keep the rate of pressure rise low enough to be acceptable to both the strength of moving parts and to the integrity of the oil films supporting the resulting loads.

But imagine that the flame front is a little slower. The temperature and population of reactive radicals continue to rise in our mixture element, and suddenly a threshold is reached. In an avalanche-like reaction, our mixture element auto-ignites. Instead of burning in the normal way, by heating of mixture near the flame, it proceeds by an entirely different mechanism - by the propagating pressure wave of the reaction itself, jostling molecules apart. This process - detonating combustion - moves at the local speed of sound, which because the gas is now very hot, is extremely fast - several thousand feet per second. This shock wave - for that is what it is - now hits the inside of the combustion chamber with a metallic and audible knock.

Normally the internal surfaces of an engine exposed to combustion heat are to a useful degree insulated by the thin layer of gas next to them that has become stagnant by losing its motion in frequent collisions with that surface. Now the shock wave from the detonation of our bit of mixture hits this layer, scouring it away and exposing the metal beneath to accelerated heating from fresh hot gas. This is why even light detonation is often accompanied by a small and unexplained rise in engine temperature. Surfaces heated in this way may be weakened enough by their new and higher temperature to be eroded - with material blasted off of them - by repeated detonation waves. Light detonation leaves the edges of pistons looking slightly sandblasted. Heavier detonation splashes off aluminum which can sometimes be seen as something like gray cigarette ash specks on the spark plug insulator. Curiously, detonation also seems to behave like chemical erosion, removing metal selectively to create tunnels into aluminum pistons or heads - often several millimeters deep. In these eroded areas the crystalline nature of the metal is revealed. Ultimately, damage of this kind may hammer ring top lands down, trapping the rings successively until combustion gas finds its way through the oil ring's drain holes. In this way, an entire face of the piston may be shortly eroded away, exposing the rings and blowing gritty piston metal into the crankcase.

Even in cases in which complete parts destruction does not take place, the hammering of detonation can damage engine bearings.

Detonation requires as a pre-condition that some part of parts of the unburned charge - generally at the outer edges of the chamber - be heated enough to bring the pre-flame reactions within it to maturity. This means that anything that increases temperature is pro-detonation - a charge made hotter by increased supercharge compression, a hotter intake tract and combustion chamber, a higher geometric compression ratio, an exhaust valve running hot because of the degraded cooling effect of poor seating.

Time is also a factor, so earlier ignition timing and engine operation at heavy load and lower rpm are potential culprits as well. This is why taxicab engines, burning the cheapest bulk gasoline and lugged in high gear for economy, are so often heard to detonate, The best defense against detonation is combustion so fast and efficient that it burns up the charge completely before any part of it can be heated enough to move through the pre-flame reactions to finally auto-ignite. Engineers also take care to locate the spark plug closer to hotter than to cooler parts of the combustion chamber. In this way, the unburned charge is compressed by combustion into the cooler parts of the chamber, decreasing the heating that potentially leads to detonation.

Modern auto engines are designed to generate turbulence by adequately high intake velocity, and to retain that turbulence during compression by not making the combustion chamber so tight that such motion is damped out. In Formula One, where cylinder bore may be 2 1/4 times the stroke, the vertical height of the chamber is a compromise between the need for torque-boosting high compression, and the need for a chamber roomy enough to retain the turbulence necessary for rapid combustion. In the classic large aircraft engines, their low compression ratios provide roomy chambers in which turbulence retention is excellent and combustion therefore rapid.

Detonation is suppressed also by use of knock-resistant fuels. These take the form of compact molecules that resist break-up during pre-flame heating better than do the floppier straight-chain molecules of knock-prone species such as normal heptane. Also very knock-resistant are fuel molecules based upon the six-carbon benzene ring - species such as toluene and xylidene (and of course benzene itself, which is a wonderful fuel save for its propensity to freeze solid in Minnesota winters, and to give leukemia to unfortunate Turkish shoe workers who were obliged to use it as a rubber solvent).

Anti-knock additives such as tetra-ethyl lead function as reverse rate catalysts, making it easier for reactive molecular fragments to resume their former benign forms, thereby slowing their rate of population increase with temperature. TEL acts to "buy time", during which normal combustion may go to non-violent completion. Unfortunately, while adding a gram of TEL per gallon has a useful effect, adding a second gram does not double it, and each additional gram added has an even smaller effect.

In the late 1920s many aircraft engine designers had all but given up on the spark-ignition gasoline engine because detonation set such a low limit on power. This was a result of poor cylinder and head cooling, lack of supercharge air cooling before induction, the poor anti-knock quality of fuels, and the high temperature at which exhaust valves operated. Diesel engines faced no such limits at the time, and were looked upon as the logical future. Then everything changed; TEL was discovered by Thomas Midgley at Kettering's Dayton Electrical Laboratory (Delco), internally-cooled valves were perfected by S. D. Heron, and improved casting materials and methods made it practical to air-cool engine cylinders at higher specific powers.

Today, because available gasoline is comparable in anti-knock rating to what was available to the USAAC 69 years ago, Diesel engines for light aircraft are once again under vigorous development.