

Preignition & Autoignition, Deflagration & Detonation.

Green Hulk PWC Performance Forums - Technical Articles and Explanations.

Books will tell you what Harry Ricardo learned back in 1918; that detonation is not the same as preignition. Preignition is lighting of the charge before the spark, by some hot object in the combustion chamber usually the overheated center or earth electrode of a spark plug whose heat range was too hot for the application.

Preignition soon provokes detonation, so the confusion is understandable.

Detonation, by contrast, is self ignition of some of the last parts of the charge to burn the so-called "end gas" out at the edges of the combustion chamber after the spark has already ignited and mostly burned the charge. This self igniting endgas does not then burn normally, as a flame front spread by turbulence at the usual speed of a few meters per second. This gas burns at the local speed of sound, which is very high because the temperature & pressure is high.

The speed of sound in air at 1.0 bar @ 0°C = 342m/sec. It rises roughly in proportion to the square root of pressure and absolute temperature increase so for 10:1 compression and the associated rise in temperature we can have velocities in excess of 1000m/sec – we are into high explosive territory.

This form of combustion, called detonation, forms a shock front, a sudden jump in pressure that propagates at such explosive velocities.

When it hits parts, it hits hard. If we hear it, if at all, it is as a high, dry, irregular clicking, not unlike the reverberating sound of rocks struck under water. Detonation's pressure front can damage bearings by its hammering shock, but the real problem is what it does to an engine's natural, internal insulation.

In any situation in which gases move next to solid surfaces, there is a layer of significant thickness that remains largely stagnant because it is attached to the surface.

In internal combustion engines, this boundary layer quite effectively shields the engine's metal internal surfaces from direct contact with combustion gas, keeping them cooler than they would otherwise be.

When detonation begins even light detonation (and particularly light detonation in the squish bands) this boundary layer is scoured off by the impacting shock waves, and heat transfer from hot gas to cool metal accelerates. In only a very few detonating cycles, piston temperatures rise dramatically, and the rest of the parts exposed to combustion gas aren't far behind.

(P.S. "light detonation" is akin to a "mild heart attack".)

What is strange to many people is that as this happens, exhaust gas temperature falls. This seems odd because people associate detonation with heat, and heat with failure. But the fact is that as you lean an engine down, its exhaust temperatures peak, not when the mixture becomes lean (that is, too little fuel to react with all the oxygen in the air charge), but when the mixture is chemically perfect. Exhaust gas temperature falls when detonation begins because the engine's internal insulation is destroyed; that being so, some heat that would otherwise go out the exhaust is now being diverted into the piston, head, and cylinder walls. Because those parts are getting hotter, the exhaust gas becomes colder.

Those of us who began racing motorbikes before water cooling arrived tend to think that engines get hotter the more we jet them down. With air cooling, this seems to be true, but isn't. The engine runs cool when it's rich because the extra fuel reduces peak flame temperature, and as we lean down towards chemically correct mixture, the engine runs hotter and hotter. Often, in a modified engine with high compression, this detonation begins even before we reach correct mixture and peak flame temperature. Then the engine really heats up. This leaves us with the idea that leaning down the mixture raises engine temperature, in a straightline relationship.

Basic thermodynamic efficiency is calculated on the difference between inlet and exhaust temperatures so hotter means more power – but.....

Now we know, from our experiences with water-cooled engines, that power, engine temperature, and exhaust gas temperature all rise as we lean down until we go beyond chemically correct mixture. When we do, power, engine temperature, and exhaust gas temperature all begin to fall again. We couldn't see this before, with air-cooling,

because the power we were making was overwhelming the engine's cooling ability. But it makes perfect sense because heat release in combustion depends upon finding enough oxygen so that each and every hydrogen and carbon atom in the fuel is completely reacted to form water and carbon monoxide. Any fuel left over is potential chemical energy unreleased which is why running over-lean makes less power. On a well cooled engine that is not detonating, you can lean down until it starts to slow down. However most modern engines will start to detonate before we reach this situation so we need to be extremely careful.

Now back to detonation. The above explanation is the common one, but it leaves important questions unanswered. For example, why does detonating combustion travel at the local speed of sound, and not at normal burning speed? Why does the endgas auto ignite, rather than simply wait there like a stand of trees in the path of a forest fire? Understanding how this comes about helps to understand how the variables that affect detonation generate their effects and it helps to fend off the phenomenon that sets the upper limits on performance.

There are two basic forms of combustion, deflagration and detonation. In deflagration, the propagation of combustion is carried out by simple convection; the hot combustion gas heats what is ahead of it, raising its temperature to the ignition point.

Because this process of heating what lies ahead takes time, it is relatively slow. The burning of a quiescent gasoline air vapor is in fact slow (less than a meter per second). Combustion in an engine cylinder is much faster than this because of compression pressure, adiabatic temperature rise during compression & turbulence, which so wrinkles the flame front that its area becomes hugely enlarged.

Turbulence is a major factor in propagating the flame front and is mostly produced by the squish zones and inlet configurations that "swirl" the mixture. The propensity for detonation to occur in the squish zones (in high performance / high compression engines) is however a problem that needs careful consideration.

Detonation is a different animal than ignition, and not all gaseous mixtures will support detonation. It is a form of combustion in which the unburned material is heated to ignition at least partly by shock compression, as the detonation wave moves at the local speed of sound through the medium. This has to happen very quickly, so fuels with simple molecules or those with low stability lend themselves to this form of combustion.

Now how does the endgas ignite by itself? It does so when its temperature is raised by any combination of effects to some critical value in the range of 450-550 C°.

In a running engine, air is drawn in at some ambient temperature, and this air then begins to pick up heat from the hot internal engine surfaces it contacts. Finally it enters the actual cylinder, where it is heated by even hotter surfaces. Trapped there, it is heated again by the process of compression.

In this heating process, some little discussed chemical reactions begin to occur in the fuel. Called preflame reactions, these take the form of slow, partial breakdown of the least durable types of fuel molecule. Fuel hydrocarbons have three basic forms; straight carbon chains, branched chains, and ring structures. Temperature is a measure of average molecular activity, but there are always some gas molecules moving significantly faster than the others. These faster moving molecules hit and break some of the less durable fuel molecules, dislodging some of their more weakly bonded hydrogen atoms. This released hydrogen is very reactive (normally hydrogenous travel in bonded pairs, but this is atomic hydrogen) and instantly pairs with an oxygen from the air to form what is called a radical, a chemical fragment that is highly reactive because it contains an unpaired electron. Its attraction for the missing electron is so great that it can snap one out of other chemical species it happens to collide with, thereby breaking it down as well.

At some point in the compression stroke, the spark ignites the mixture and combustion begins. The burned gases, being very hot, expand against the still unburned charge, compressing it outward into the squish band. This compression rapidly heats the unburned charge even more, accelerating the preflame reactions in it. As a rule of thumb, the rate of chemical reaction doubles every 10°C. All this while, the population of reactive molecular fragment radicals is increasing in the unburned endgas. If this process of heating takes long enough, and reaches a temperature high enough, this population of radicals becomes great enough that its own reaction rate one radical creating more and more through further reactions accelerates into outright combustion. This is autoignition.

Now why does this heated, chemically changed endgas detonate instead of simply burning? The fuel in the endgas is no longer ordinary gasoline. The preflame reaction that have taken place in it have changed it into a violent explosive much like a mixture of hydrogen and air, or acetylene and oxygen. It is in a hair-trigger state, being filled with reactive fragments from preflame reactions. When it autoignites spontaneously, combustion accelerates almost instantly because the material is so easily ignited now. The combustion front accelerates to the local speed

of sound, igniting the material it passes through simply by suddenly raising its temperature, through the shock wave it has now become.

Stopping The Show

Anything that contributes to lowering the temperature that the endgas reaches will make detonation less likely. Anything that slows the process of conversion from normal gasoline into a sensitive explosive, will make detonation less likely. Anything that speeds up combustion, so that is it completed before the conditions needed for detonation can develop fully, will make detonation less likely.

Therefore the following will work;

- (1) Lower intake temperature
- (2) Lower throttle position, lower volumetric efficiency, or reduced turbo boost the less mixture that enters the cylinder, the less it is heated by compression.
- (3) Lower intake pipe, crankcase, and/or cylinder, piston, or head temperatures.
- (4) Lower compression ratio. The less you squeeze it, the less it is heated.
- (5) A more breakdown resistant fuel, such as toluene or isooctane. If straight chain molecules are not present, the fuel will not be broken down so rapidly by preflame reactions.
- (6) A negative catalyst something that will either pin down active radicals or convert them into something harmless. Tetraethyl lead, MMT, or other antiknock compounds are the medicine.
- (7) Retarded timing shortens the time during which preflame reactions can take place.
- (8) Incylinder turbulence or anything else that will speed up combustion (faster burning fuel such as benzene). This works by completing combustion before the time bomb of preflame reactions cooks long enough to cause autoignition.
- (9) Higher engine rpm This simply shortens the time during which the mixture is held at high temp. In Honda experiments in the 1960's, they found that an engine's octane requirements began to decrease steadily over 12,000 rpm, and were under 60 octane up near 20,000. In a more accessible example, note that engines knock when they are "lugged" run at low rpm, wide open throttle and stop knocking promptly when you shift down a gear and let the engine rev up more. This stops detonation by not allowing enough time for the reactions that cause it.
- (10) Redesigning troublesome exhaust pipes. Some pipes give great numbers on the dyno, but can't be used because they cause seizures. They either simply overcharge the engine in some narrow rpm band (pushing it into detonation just as too much turbo boost would do), or back pump mixture from the header pipe that has picked up too much heat (this is why nobody heat wraps header pipes anymore).
- (11) Avoiding excessive backpressure. Exhaust pipes always create back pressure, but the more there is, the higher the fraction of hot

exhaust gas that will be unable to leave the cylinder during exhaust. Its heat, added to the fresh charge that next enters the cylinder, may push the engine over the line into detonation. Sometimes a one or two millimeter reduction in (two-stroke) tailpipe ID will get you a couple of extra horsepower, but it may also push enough extra heat into the charge to make the engine detonate after a few seconds.

The number of ways of playing footsie with detonation is endless, but nothing works every time. This guarantees that we will never be bored, and will never run out of seized pistons.

Race Fuel Octane Explained

Wrenching with Rob--Chemical Soup: The Meaning of Gas.

In many high-performance situations, drivers clamour for higher octane fuels, thinking this will give them additional horsepower and, thus, an advantage over the competition. But this is not the case - adding higher-octane race fuel may actually produce less horsepower.

Here's why:

Iso-Octane is one of the principal chemical ingredients of gasoline – which is actually a witches brew of over 300 chemical compounds (Chemical Soup).

Pure Iso-Octane tends to burn without detonating whilst another compound – n-Heptane – tends to explode under almost any conditions.

The Octane number represents an equivalent fuel to a mixture of these two compounds

i.e. 95 Octane is equivalent to a mixture of 95% Iso-Octane and 5% n-Heptane

So where the hell does 102.6 Octane come from since by this logic there can be no Octane rating higher than 100.

Well since Octane rating was primarily determined by testing in a variable compression engine against comparative chemically pure Octane / Heptane mixtures it was discovered that some mixtures perform beyond the 100% Octane rating and so by extrapolation we get higher index numbers.

Numbers determined by testing on an industry standard variable compression ratio motor are termed MON = Motor Octane Number such that if “knocking” occurs at 10:1 (illustrative value only) on 100% Octane any other fuel that produces knocking at 10:1 regardless of its composition is also rated 100 Octane.

(Sometimes the term EON = Engine Octane Number is used.)

If knocking was to occur at 11:1 this would then be rated at 110 Octane

The petroleum industry has come a long way and can now analyse spectrographically the various compounds in any fuel sample and can calculate its Octane rating based on the known values for these compounds processed through a series of equations & established heueristics.

This is termed RON = Research Octane Number.

Octane, as you can see, is **not** a measure of how much power--or, more correctly, specific energy--is contained in a fuel. And remember that leaded high-octane race fuels burn slower than most unleaded fuels, and may reduce performance in stock or lightly modified engines. A high octane rating itself, however, does not mean that the fuel is slow burning. Hence, it has no direct bearing on the power characteristics of the fuel.

The knock tendency (and hence, the Octane rating) of a fuel is a function of the amount of free radicals present in the fuel prior to ignition and can be reduced by the addition of aromatic hydrocarbons (such as toluene), oxygenated hydrocarbons (such as Methanol & Ethanol) all of which have flame speed retardent features and

other additives such as organo-metal compounds like tetra ethyl lead or MMT (Methylcyclopentadienyl Manganese Tricarbonyl) behave like negative catalysts which inhibit or capture free radicals. All of these boost Octane numbers.

Although some racing organizations still use maximum octane number as the discriminating factor for fuel legality, it is really not appropriate for racing purposes.

Instead one should look at the amount of energy (heat) released in the burning of a particular fuel. This is described by the specific energy of the fuel (calorific value).

This quantity describes the amount of power one can obtain from the fuel much more accurately. The specific energy of the fuel is the product of the lower heating value (LHV) of the fuel and molecular weight of air (MW) divided by the air-fuel ratio (AF):

Specific Energy = $LHV \cdot MW / AF$

For example, for gasoline $LHV = 43 \text{ MJ/kg}$ and $AF = 14.6$, while for

Methanol $LHV = 21.1 \text{ MJ/kg}$ (less "heat" than gasoline) and $AF = 6.46$ (much richer jetting than gasoline).

Using the above formula we see that methanol only has a 10% higher specific energy than gasoline!

This means that the power increase obtained by running methanol, with no other changes except jetting, is only 10%. Comparing the specific energy of racing and premium pump gas you can see that there is not much, if any, difference. Only alcohols (such as methanol or ethanol) have a slightly higher specific energy than racing or pump gas.

Other oxygen-bearing fuels, besides the alcohols and nitromethanes, such as the new ELF fuel, will also produce slightly more power once the engine is remapped. However, at \$15.00 to \$20.00 at gallon for the fuel the reportedly minor (1% - 2%) improvement is hardly worth the cost for the average racer.

The real advantage of high Octane racing gasolines comes from the fact that they will tolerate higher compression ratios (due to their higher octane rating) and thus indirectly will produce more power since you can now build an engine with a higher compression ratio. Also, alcohols burn cooler than gasoline, meaning even higher compression ratios are possible with them, for even more power.

The bottom line here is that, in a given engine, a fuel that **doesn't knock** will produce the same power as most expensive racing gasolines.

However, it sometimes happens that when you use another fuel, the engine suddenly seems to run better. The reasons for this are indirect:

First, the jetting may be more closely matched to the new fuel. Secondly, the new fuel may improve the volumetric efficiency (that is, the "breathing") of the motor. This happens as follows:

Basically a fuel that quickly evaporates upon contact with the hot cylinder wall and piston crown will create additional pressure inside the cylinder, which will reduce the amount of fresh air/fuel mix taken in. This important--but often overlooked--factor is described by the amount of heat required to vaporize the fuel, described by the 'enthalpy of vaporization' (H), or 'heat of vaporization' of the fuel.

A high value of H will improve engine breathing, but the catch is that it leads to a different operating temperature within the engine. This is most important with two-strokes, which rely on the incoming fuel/air mix to do much of the cooling--even modern water-cooled two-strokes rely on incoming charge to cool the piston.

For two-strokes a fuel that vaporizes, drawing a maximum amount of heat from the engine, is essential--the small variations in horsepower produced by different fuels is only of secondary concern.

Also important is the flame speed: Power is maximized the faster the fuel burns because the combustion pressure rises more quickly and can do more useful work on the piston.

Flame speed is typically between 35 and 50 cm/sec. (uncompressed hydrocarbon fuel mixtures)

This is rather low compared to the speed of sound, at which pressure waves travel, or even the average piston speed.

It is important to note that the flame propagation is greatly enhanced by turbulence (as in a motor with a squish band combustion chamber).

The most amazing thing about all this is that you can get the relevant information from most racing gasoline manufacturers. Then, just look at the specification sheet to see what fuel suits you best:

Hot running motors and 2-strokes should use fuels with a value of "H" that improves their cooling, while more power (and more heat) is obtained from fuels with a high specific energy.

By the way, pump gas has specific energies which are no better or worse than most racing gasolines. The power obtained from pump gas is therefore often identical to that of racing fuels, and the only reason to run racing fuels would be detonation problems, or, since racing fuels are often more consistent than pump gas--which racers call "chemical soup"--a consistent reading of the spark plugs and exhaust pipe.

Detonation, Knocking, Pinging & Things That Go Bump In Your Engine

The problem of detonation, commonly referred to as "knock," which is a very serious and detrimental problem when it occurs - usually the pressures exerted onto the piston top during detonation are much larger (but of a shorter duration, like a pressure spike) than the mean combustion pressure.

Nevertheless they are very detrimental to engine life, as the continual high shock loading of the piston, rod, crankshaft and bearings is quite destructive.

Detonation is the result of an amplification of pressure waves, such as sound waves, occurring during the combustion process when the piston is near top dead center (TDC).

The actual "knocking" or "ringing" sound of detonation is due to these pressure waves pounding against the insides of the combustion chamber and the piston top, and is not due to 'colliding flame fronts' or 'flame fronts hitting the piston or combustion chamber walls.'

Let's look in some detail at how detonation can occur during the combustion process:

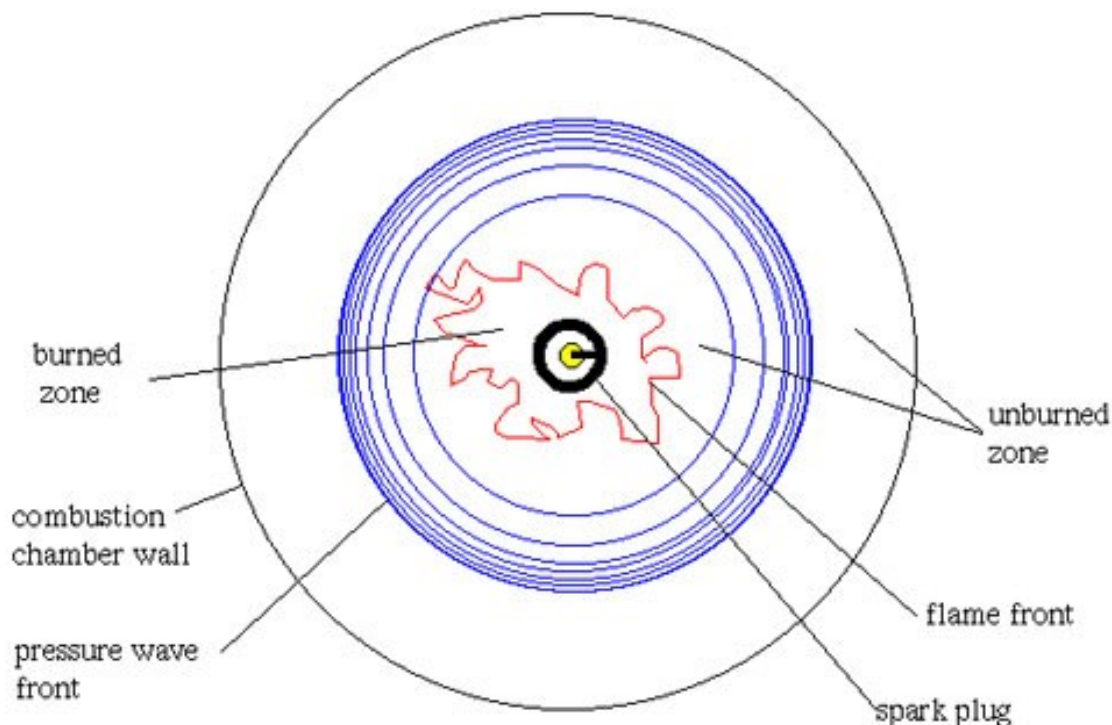
First, a pressure wave, which is generated during the initial ignition at the plug tip, races through the unburned air-fuel mix ahead of the flame front.

Typical flame front speeds for a gasoline/air mixture are on the order of 40 to 50 cm/s (centimeters per second), which is very slow compared to the speed of sound, which is on the order of 300 m/s. In actuality, the true speed of the outwards propagating flame front is considerably higher due to the turbulence of the mixture. Basically, the "flame" is carried outwards by all the little eddies, swirls and flow patterns of the turbulence resident in the air-fuel mix.

This model of combustion is called the "eddy burning model" (Blizzard & Keck, 1974).

Additionally, the genus of the flame front surface - that is the degree of 'wrinkling' - which usually has a fractal nature (you know, those weird, seemingly random yet oddly patterned computer drawings), is increased greatly by turbulence, which leads to an increased surface area of the flame front. This increase in surface area is then able to burn more mixture since more mixture is exposed to the larger flame front surface. This model of combustion is called the "fractal burning model" (Goudin, F.C. et al. 1987, Abraham et al. 1985). The effects of this are observed in so-called "Schlieren pictures," which are high-speed photographs taken through a quartz window of a specially modified combustion chamber (Fig. 1, below).

Fig. 1 - Combustion Process - Top View



Schlieren pictures show the various stages of the combustion process, in particular the highly wrinkled and turbulent nature of the flame front propagation (initially called the flame 'kernel').

A higher degree of turbulence, and hence a higher "effective" flame front propagation velocity can be achieved with a so-called squish band combustion chamber design.

Sometimes a swirl-type of induction process, in which the incoming mixture is rotating quickly, will achieve the same goal of increasing the burn rate of the mixture.

As a general rule-of-thumb the pressure rise in the combustion chamber during the combustion phase is typically 20-30 PSI per degree of crankshaft rotation.

Once the pressure rises faster than about 35 PSI/degree, the engine will run very roughly due to the mechanical vibration of the engine components caused by too great of a pressure rise. Sometimes, the pressure wave can be strong enough to cause a self ignition of the fuel, where free radicals (e.g. hydroxyl or other molecules with similar open O-H chains) in the fuel promote this self ignition by the pressure wave. As a general rule-of-thumb the pressure rise in the combustion chamber during the combustion phase is typically 20-30 PSI per degree of crankshaft rotation. However, this can still occur even without the presence of free radicals; it just won't be quite as likely to happen. This is why high octane fuels, with fewer of these active radicals, can resist detonation better. However, even high octane fuel can detonate - not because of too many free radicals - but because the drastic increase in cylinder pressure has increased the local temperature (and molecular speed) so high that it has reached the ignition temperature of the fuel. This ignition temperature is actually somewhat lower than that of the main hydrocarbon chain of the fuel itself because of the creation of additional radicals resulting from the break-up of the fuel's hydrocarbon chains in intermolecular collisions.

Detonation usually happens first at the pressure wave's points of amplification, such as at the edges of the piston crown where reflecting pressure waves from the piston or combustion chamber walls can constructively recombine - this is called constructive interference to yield a very high local pressure. If the speed at which this pressure build-up to detonation occurs is greater than the speed at which the mixture burns, the pressure waves from both the initial ignition at the plug and the pressure waves coming from the problem spots (e.g. the edges of the piston crown, etc.) will set off immediate explosions, rather than combustion, of the mixture across the combustion chamber, leading to further pressure waves and even more havoc.

Whenever these colliding pressure fronts meet, their destructive power is unleashed on the engine parts, often leading to a mechanical destruction of the motor.

The pinging sound of detonation is just these pressure waves pounding against the insides of the combustion chamber and piston top. Piston tops, ring lands and rod bearings are especially exposed to damage from detonation. In addition, these pressure fronts (or shock waves) can sweep away the unburned boundary layer of air-fuel mix near the metal surfaces in the combustion chamber. (see figure 2 below)

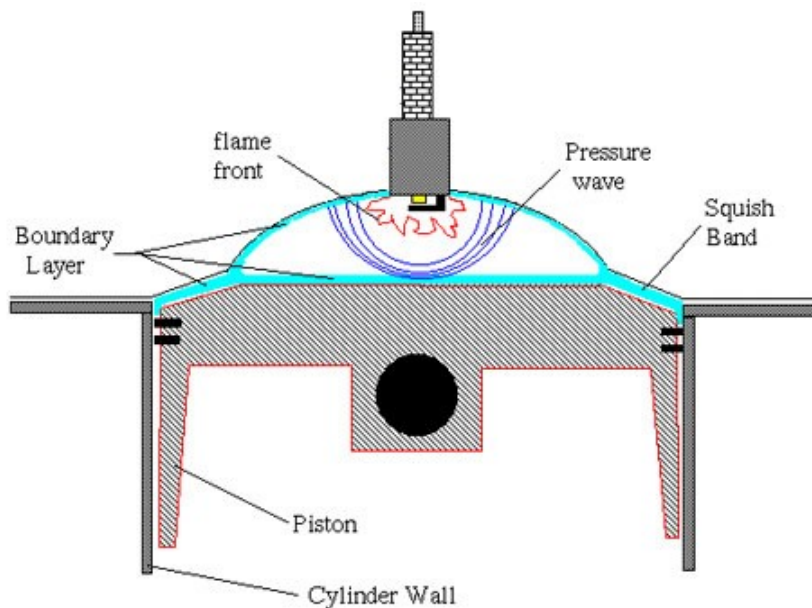


Fig. 2 - Combustion Chamber Side View

The boundary layer is a thin layer of fuel-air mix just above the metal surfaces of the combustion chamber (see figure 2, above).

Physical principles (aptly called boundary conditions) require that under normal circumstances (i.e. equilibrium combustion, which means "nice, slow and thermally well transmitted") this boundary layer stays close to the metal surfaces. It usually is quite thin, maybe a fraction of a millimeter to a millimeter thick. This boundary layer will not burn even when reached by the flame front because it is in thermal contact with the cool metal, whose temperature is always well below the ignition temperature of the fuel-air mix.

Only under the extreme conditions of detonation can this boundary layer be "swept away" by the high-pressure shock front that occurs during detonation. In that case, during these "far from equilibrium" process of the pressure-induced shock wave entering the boundary layer, the physical principles alluded to above (the boundary conditions) will be effectively violated.

The degree of violation will depend on (a) the pressure fluctuation caused by the shock front and (b) the adhesive and cohesive strength of the boundary layer. These boundary layers of air-fuel mix remain unburned during the normal combustion process due to their close proximity to the cool metal surfaces and act as an insulating layer and prevent a direct exposure of metal to the flame. Since pressure waves created during detonation can sweep away these unburned boundary layers of air-fuel mix, they leave parts of the piston top and combustion chamber exposed to the flame front. This, in turn, causes an immediate rise in the temperature of these parts, often leading to direct failure or at least to engine overheating.

Scientists and engineers have recently begun to understand combustion in much greater detail thanks to very ambitious computer simulations that model every detail of the combustion process (Chin et al. 1990). Basically, a complete computer model includes a solution to the thermodynamical problem, that is a solution to the conservation equations and equation of state, as well as a mass burning rate and heat transfer model. In addition, a separate code (called a chemical kinetics code) models the chemical processes which occur during combustion and sometimes juggles several thousand different chemical species, some in vanishingly small concentrations! Needless to say these codes require huge amounts of memory and CPU time that only the largest supercomputers in the world can provide. They are far beyond the reach of the private individual and usually only employed by large research institutions or major car manufactures.

Here's a brief recital of the question we received:
Someone asked:

Rob, I read your "Chemical Soup: The Meaning of Gasoline." Quick question if you have the time... You mentioned that "flame propagation is greatly enhanced by turbulence." Should this be a consideration when an engine is ported? Can turbulence be enhanced by porting without losing the intake flow?

Unless the ports are specifically designed for a strong swirl-type induction process, the turbulence created during the intake process is not very affected by porting. This is true as long as one sticks with the same general port layout. However, drastic porting changes may increase or decrease the turbulence in the combustion chamber, but it is quite difficult to say anything definite. I think that any improvement gained by porting the engine is likely to be far greater than any possibly detrimental effect the porting may have had on turbulence.

The biggest benefit is obtained by reducing the squish band to its safe minimum (about 0.020-0.040 in, depending on the particular engine used). This will have a far greater effect on increasing the turbulence in the combustion chamber than any other modification.

Mike Meagher (meagher@pentec.wa.com) wondered about the effects of the squish band.

It is important to realize the two important functions of reducing the squish band clearance: (a) to enhance turbulence due to rapid ingestion of gas into the combustion chamber, hence increasing the burning rate of the mixture and (b) to reduce the volume of the unburned gas in the boundary layer of cool gas near the piston top and cylinder head surfaces. Typically, gas trapped in the squish area doesn't burn, even if the squish band clearance is relatively large. The cooling effects of the large surface-area-to-volume ratio of this region will prevent any ignition of the fuel-air mix therein, even if the squish band clearance is rather large. Hence any gas caught in the squish band will not be burned near TDC when it does the most good, but later during the combustion process when one cannot extract as much work from the late-burning gases. The amount of gas trapped in the squish band can actually be a substantially greater amount than just the relative volume of the squish band because the pressure wave from the ignition process literally crams a lot of the unburned gas into crevice areas like the squish band. Reducing the squish band clearance will decrease the amount of unburned gas substantially, leading to more complete and faster combustion, lower emissions and improved power.

David Goodenough (dg@pallio.sf.ca.us) asked:

Suppose I mix one gallon of 87 octane pump gas, and one gallon of 92 octane pump gas. Are you telling me that instead of two gallons of 89.5 octane gas I have something closer to 92 (like between 90 and 91)?

The mixed gas' octane rating will in general not be a linear function of the original constituents' octane ratings. Neither will it be a simple function in most cases. Rather, the octane rating becomes a quite complicated, non-linear function of some very small amounts of free radicals, such as hydroxyl and hydroxyl peroxide, in the fuel. Essentially, there is no simple analytic way to predict the final octane rating of a fuel; rather, extensive tests with a calibrated engine are necessary (see MON and RON explanations above).

Free Radical Nascent Oxygen O As Opposed to O₂

When the free radical Oxygen atom is produced (termed nascent Oxygen) it is highly aggressive and will quite happily eat your pistons.

Aluminium is the "fuel" used in the Space Shuttle's solid fuel boosters and it is oxidised by free radical O liberated from the Ammonium Perchlorate oxidiser.

Nascent Oxygen is also released during underwater cavitation of propellers and it is capable of eating cold bronze, hot Aluminium is a marshmallow by comparison.

So under condition of detonation, the boundary layer is swept away and the Aluminium piston is exposed to both the combustion's furnace heat, the physical abuse of the explosive shockwave and free Oxygen radicals looking for lunch.

In NOS boosted engines the Oxygen released from the NOS is nascent and lots of it – so if you have detonation with NOS its goodbye pistons – real quick.

Obviously NOS without sufficient fuel is also a recipe for disaster. The surplus nascent Oxygen will induce detonation & will light off the free carbon deposits on the piston crown at incandescent temperatures followed by a dessert helping of Aluminium from the piston. Destruction is very rapid – so use a knock sensor.

Detonation In The Squish Band

What happens in the squish band ? Practically anything from nothing at all to all-out thermonuclear warfare with your engine.

Ideally we would like our pistons to compress the fuel mixture into a the compression chamber into a spherical ball shape with the ignition point at its centre for all the fuel mixture to be within the shortest possible distance from ignition because of the relatively low flame propagation speeds.

Alas what we would like to do and what we can do are usually quite different.

So a compromise is to use a squish zone, this forces the bulk of the compressed mixture to be in closer proximity to the source of ignition whilst simultaneously creating massive turbulence which will greatly enhance combustion.

It would seem obvious that you could then make the squish bands as wide (area) and thin (gap to cylinder head) as possible at TDC.

Again reality constricts us and in multivalve engines, great swathes of potential squish area are sacrificed to valve pockets.

O.K. so then lets make our remaining squish areas as thin as possible at TDC – Nothing wrong with that idea but in high performance engines running close to detonation, we might run into detonation within the squish band.

Such detonations can be highly localised – ie micro-detonations restricted to the edge of the piston, valve pocket edges etc. – but will spread as the detonation induced damaged surface becomes a sea of preferential ignition (detonation) points.

This normally presents itself as a sharkskin finish on piston and even the cylinder head and is usually fatal.

This is sometimes termed “silent knocking / pinging”, because of its localised nature may not be noticeable – in some cases even electronic knock sensing devices cannot distinguish it from background “noise” – you certainly won't pick it up with your ears inside a full face helmet with ear plugs over the roar of a racing engine at full song.

In a normal engine the fuel mixture in the squish bands will not even light off because of local cooling effects in the narrow squish band and will only burn (less effectively) later in the cycle.

However during compression the squish zone can become locally higher in pressure & temperature (particularly at higher rpm's and high performance engines) and induced autoignition and subsequent detonation can occur within the squish zone.

Similarly the advancing pressure wave from normal combustion can “cram” the squish zone into detonation as can constructive interference pressure waves etc. etc. Again those valve pockets create multiple pathways into the squish zone where constructive interference can lead to autoignition / detonation.

The problem with this mode of failure is that you can have an engine that has been working well for some time and then suddenly self-destructs from pre-ignition for no apparent reason.

There will be a reason – any of the following or combination thereof may have pushed your mill over the edge :-

Lower Octane fuel

Hotter than average weather

Higher Atmospheric pressure (gone to salt lake maybe ?)

Slightly higher boost (what the hell – give it a little more ?)

So we are faced with a problem - How thin can we make the squish bands ??

Most references quote 1.0 to 1.5mm but I have seen some high performance engine builders go as far as 2.0mm they were clearly uneasy with thinner squish bands.

Certainly my own experience with repeated detonation failure in the squish bands on both two and four stroke engines has been under 1.2mm

Warning signs

Sharkskin finish (even minute areas) appearing on piston edges, valve pocket edges, anywhere in the squish zones on the piston or cylinder head.

Localised scouring of carbon deposits on the piston or cylinder head – examine with a magnifying glass @ 10X

“Piston Ash” on the spark plug.

REFERENCES

Abraham, J. et al., 1985, "A Discussion of Turbulent Flame Structure in Premixed Charges", SAE paper 850345

Blizzard, N.C. and Keck, J.C., 1974, "Exp. and Theo. Investigation of Turbulent Burning Model for Internal

Combustion Engines", SAE paper 740191

Chin et al., 1990, "Diagnostics and Modeling of Combustion in Internal Combustion Engines," JSME, Tokyo, p. 81-86

Goudin, et al., 1987, "An Application of Fractals to Modeling of Premixed Turbulent Flames", Combustion and Flame 68, p.249-266

Common Fuel Types / Names

AVGAS

Avgas is gasoline fuel for reciprocating piston engine aircraft and is not to be confused with [jet fuel](#). As with all gasolines, avgas is very volatile and is extremely flammable at normal operating temperatures. Procedures and equipment for safe handling of this product must therefore be of the highest order.

Avgas grades are defined primarily by their octane rating. Two ratings are applied to aviation gasolines (the lean mixture rating and the rich mixture rating) which results in a multiple numbering system e.g. Avgas 100/130 (in this

case the lean mixture performance rating is 100 and the rich mixture rating is 130).

In the past, there were many different grades of aviation gasoline in general use e.g. 80/87, 91/96, 100/130, 108/135 and 115/145. However, with decreasing demand these have been rationalised down to one principle grade, Avgas 100/130. (To avoid confusion and to attempt to eliminate errors in handling aviation gasoline, it is common practice to designate the grade by just the lean mixture performance, i.e. Avgas 100/130 becomes Avgas 100). More recently, an additional grade was introduced to allow one fuel to be used in engines originally designed for grades with lower lead contents: this grade is called Avgas 100LL, the LL standing for 'low lead'. It is also "low Benzine".

All equipment and facilities handling avgas are color coded and display prominently the API markings denoting the actual grade carried. Currently the two major grades in use internationally are Avgas 100LL and Avgas 100. To ease identification the fuels are dyed; for example Avgas 100LL is colored blue, while Avgas 100 is colored green.

Other Colours

Red 80/87

Green 110/130 (Referred to as "Grape Juice" in US aviation slang.

Purple 115/145 US Military Grade

Avgas generally has a lower Enthalpy of Evaporation – they try to keep the volatiles down for fire risk reasons – therefore Avgas has less cooling effect. However since many of these volatiles give higher octane numbers the process is counterproductive so unlikely to be significant.

Aviation Gasoline

Aviation gasoline, or Avgas, is the fuel used in aircraft powered by reciprocating, rather than turbo-jet or turbo-prop engines. Avgas is similar to conventional motor gasoline; however, there are several important differences. Avgas is generally less volatile and has a lower freezing point than conventional gasoline. Common additives to Avgas include alkyl-lead anti-knock additives, metal deactivators, color dyes, oxidation inhibitors, corrosion inhibitors, icing inhibitors, and static dissipaters. Three grades of Avgas are currently available in the U.S. and are characterized by their anti-knock characteristics. American Society for Testing and Materials (ASTM) Grades 100 and 100LL Avgas have octane ratings of 100 and are the most widely available. These grades contain about 1.0 and 0.5 grams per liter of tetra ethyl lead, respectively, considerably more than automotive gasolines currently in use.

Important Terms

Alcohol - An organic compound that has an oxygen/hydrogen (OH) group bonded to a hydrocarbon group.

Biodegradation - The alteration of petroleum by living microorganisms that naturally reside in the environment.

Boiling Point - The temperature at which a liquid changes to a vapor or gas.

Crude Oil - Petroleum as found in the earth, before it is refined into petroleum products.

Gasoline - A refined petroleum product used as fuel for reciprocating engines, primarily automobiles.

Hydrocarbons - Organic compounds composed of only carbon (C) and hydrogen. Refined petroleum products are complex mixtures of hydrocarbons. Alkanes are saturated hydrocarbons in which all C-C bonds are single bonds. Alkenes are unsaturated hydrocarbons that have at least one C-C double bond. Aromatics are hydrocarbons that have a C6 ring analogous to that of benzene.

Kerosene - A colorless, low-sulfur petroleum product that burns without producing much smoke. It is the primary ingredient in most jet fuels.

LNAPL (Light Non-Aqueous Phase Liquid) - a low-solubility liquid that "floats" on water. Gasoline ("free product") behaves as a LNAPL when in contact with water.

Naptha - A refined petroleum product used as a solvent, cleaner, and gasoline component.

Petroleum - A naturally occurring, oily, flammable liquid composed of hydrocarbons and found associated with gas in natural underground reservoirs.

Vapor Pressure - The pressure at which a liquid and its vapor are in equilibrium at a given temperature. The more volatile a liquid and the lower its boiling point, the higher its vapor pressure. The vapor pressure of a liquid also increases with its temperature.

Viscosity - The degree to which a fluid resists flow under a standard force. The more viscous a liquid, the more resistant it is to flow. Generally, viscosity decreases as the temperature of a liquid increases.

Volatility - A measure of how quickly a substance forms a vapor at ordinary temperatures and pressure
Characteristics Common to Fuels

Fuel Manufacture

This section presents basic information about petroleum-based fuels in general and some of the many physical and chemical properties they share. Properties that may be used to characterize environmental contamination caused by one category of fuel in comparison to another are discussed in later sections.

Petroleum fuels ignite and burn readily, and produce a great deal of heat and power in relation to their weight. The one composition requirement common to all petroleum fuels is that they consist entirely of hydrocarbon molecules (hydrogen and carbon) except for small amounts of impurities and/or additives.

The refining of crude oil, also known as fractional distillation, produces a range of petroleum compounds that are primarily characterized by their boiling points and molecular weights. Short chain, single ring, or "light" hydrocarbons, are more volatile, less viscous, and have lower boiling points than long chain, multiple ring, or "heavy" hydrocarbons. Denoting the number of carbon atoms (CX) in a hydrocarbon molecule is a way to describe its weight relative to other hydrocarbon molecules. Natural gas is composed primarily of the light hydrocarbons methane (C1), ethane (C2), propane (C3), and butane (C4). Gasoline typically contains hydrocarbons in the C4-C10 range. Kerosene and aviation fuels fall primarily into the C4-C19 range. Diesel fuels are composed primarily of hydrocarbons in the C8-C21 range. Heating oils, the most common being Fuel Oil No. 2, are similar to diesel fuels, but are less refined and fall into the heavier C15-C22 range. Lubricating oils, hydraulic fluids, tars, and other heavy residual petroleum compounds are made up of hydrocarbon molecules in the C20-C60 range and larger. Some of the heavier oil fractions are further refined by a process called "cracking" to yield increased amounts of the high-demand lighter petroleum products.

Most petroleum fuels are mixtures of hundreds of different hydrocarbon compounds. The exact number and proportions of these compounds in a particular fuel may vary; therefore, most fuels are formulated to meet general property limits, rather than a specified chemical composition. An exception to this is missile fuel, which consists of either a single synthesized hydrocarbon compound or a precise mixture of such compounds. For a particular fuel product, governing standards may limit upper and lower percentage composition of certain hydrocarbons as required to meet performance criteria. Propulsion system demands, such as fluidity, combustion properties, corrosion protection, and impurity limits, are the primary determinants of standardized fuel formulations.

Volatility is a property of fuels that affects its ability to vaporize and form a combustible mixture with air. This property results in a quantifiable characteristic called vapor pressure. Vapor pressure and volatility are important properties to be considered by designers of fuel storage and delivery systems because they can lead to unwanted evaporative fuel losses or "fugitive" vapors. Lighter fuels such as gasoline and aviation fuel tend to be more volatile and have higher vapor pressures than heavier fuels such as diesel and heating oil at the same temperature and pressure.

Fuel Impurities

Refined petroleum fuels can contain a variety of undesirable impurities that originate from the crude oil, develop during the refining process, or are introduced during shipment or storage. The most common fuel impurities are discussed below.

Gums are high molecular weight compounds containing hydrogen, carbon, oxygen, and usually sulfur and nitrogen. They are formed when the hydrocarbon molecules in stored fuels are oxidized or polymerized after exposure to air, sunlight, and/or elevated temperatures. When gums precipitate from the fuel, they can clog and

form deposits on vital engine components such as filters and injectors, causing mild to severe engine performance problems. Anti-oxidant fuel additives can prevent the formation of gums.

Metals formed during certain refining processes can oxidize and contribute to the formation of filter clogging gums in any type of fuel. This problem is addressed by using a metal deactivator additive.

Microbial contamination occurs after fuels leave the refinery since the refining process sterilizes fuel. Microbes, including algae, bacteria, and fungi feed on the fuel and use the water in the fuel for their oxygen supply. They can multiply and plug fuel filters with an odorous slime. Some of the microbes can also produce corrosive acid byproducts. Minimizing water content and treating with a biocide additive will control microbial growth in fuel.

Sediment is a common contaminant of fuels and usually consists of rust, mineral scale, sand, dirt, and other insoluble impurities. To address this problem, fuels are filtered upon delivery into bulk and operating storage systems to remove as much sediment as possible before the fuel is delivered to the end user.

Sulfur compounds can be corrosive to metals in fuel systems and are controlled by the total sulfur content limits found in the fuel specification.

Water is a very common fuel impurity. Fuel can become contaminated with water during shipping and storage. Water can condense from the fuel itself, may leak into fuel containers from the outside, or it may be present in containers before they are filled with fuel. Water in fuel may also contain other impurities that can cause corrosion problems and damage filters, pumps, and injectors. Water is denser than fuel and can be removed as it collects at the bottom of a storage container.

Fuel Additives

Fuel additives are intended to help improve fuel economy, lower maintenance costs, reduce impurities and harmful deposits, reduce exhaust emissions, and improve the overall performance and reliability of the fuel. Different fuels may be formulated with different "packages" of fuel additives. Additives may also be added to fuels during storage or at the time of fueling. Often, the precise chemical composition of many fuel additives and additive packages is proprietary to the manufacturer. Particular combinations and percent content of additives may be specified in a fuel's governing standard. Where additives are approved for use or required by American Society for Testing and Materials (ASTM) standards or military standards, the chemical composition of the additive may be more readily available. Common fuel additives include:

Alkyl Lead (Tetraethyl Lead)

Alkyl Lead was a common gasoline additive until the late 1960s used to obtain higher octane ratings and reduce engine "knock." Lead additives have been reduced or entirely phased out of most automotive gasoline formulations due to the environmental hazards associated with lead-containing exhaust emissions. As lead additives have been phased out of gasoline formulations, other oxygenating additives are now used to boost octane ratings and control knock, as well as reduce harmful exhaust emissions. Leaded automotive gasoline typically contained one or more grams per liter (>1,000 parts per million [ppm]) of alkyl lead. Today, unleaded automotive gasoline contains only a few ppm of lead. Aviation gasoline (Avgas) continues to contain significant concentrations of alkyl lead, typically at levels greater than 1,000 ppm.

MMT - Methylcyclopentadienyl Manganese Tricarbonyl

Man what a mouthful – hence MMT for short.

Another in a family of "organometals" that act as an octane booster and is now the most commonly used substitute for "Lead" in fuels. The manganese in the exhaust is not considered harmful.

Be warned however that all organometals are highly poisonous (a contact skin poison) so great care needs to be taken when handling concentrates such as various brands of octane booster available (almost all are MMT based)

You cannot buy it in bulk without registered premises that comply with handling the stuff.

Chinese Lead or Chinese Octane Booster

Iron Pentacarbonyl – often touted as a non-toxic alternative for MMT – That's hype they are both highly toxic before use and relatively non-toxic as an exhaust output.

This is commonly used in China as an octane booster – however it is thought to cause excessive engine wear particularly in racing engines.

Catalytic Converters

Lead based octane boosters are lethal to Catalytic converters. The lead forms a Eutectic (A lower melting point than either of the metals involved – like solder) and the CAT is at best poisoned to death (stops working) or worse collapses like a flan in an oven and chokes off the exhaust.

Manganese & Iron carbonyls are touted as catalyst friendly – not entirely true, the life expectancy of cats and sensors are reduced (against testing with pure gas without octane boosters) so too are sensors.

If you are racing you have almost certainly removed the cats and remapped the engine accordingly – if you are using a street legal machine be careful which additives will do the least damage.

Non-Performance Related Additives

Anti-oxidants are primarily used to prevent gum formation in gasolines and aviation fuels.

Biocides may be added to any type of fuel to kill microbes when their growth becomes a recurring problem.

Conductivity additives increase the electrical conductivity of gasolines, aviation, and diesel fuels, thereby reducing the buildup of static charges during mixing, transfer, and shipment.

Corrosion inhibitors protect against corrosion during pipeline transfer and storage of fuels. They have also been found to improve the lubricity, or capacity to reduce friction of fuels. Corrosion inhibitors are used primarily in gasolines, aviation fuels, and diesel fuels.

Detergent additives prevent the buildup of gum deposits in engines and extend fuel injector life. They also help keep fuel filters clean. Detergent additives are primarily found in diesel fuels and automotive gasolines.

Icing inhibitors are used primarily in aviation fuels to prevent the formation of ice crystals from entrapped water in the fuel at freezing temperatures encountered during high altitude flight. Icing inhibitors have also been found to be an effective barrier to microbiological growth. Diethylene glycol monomethyl ether is specified for most military aviation fuels as an icing inhibitor.

Metal deactivators prevent metal contaminants in any type of fuel from oxidizing with hydrocarbons and other compounds to form gums or precipitates.

Oxygenates are oxygen-containing hydrocarbons that are added to automotive gasoline to boost the octane rating, reduce the smog-forming tendencies of exhaust gases, and suppress engine knock. The increased oxygen content promotes more complete combustion, thereby reducing tailpipe emissions. Common oxygenating additives are methyl tertiary butyl ether (MTBE) and ethanol.

Thermal stability additives reduce fuel fouling of critical jet engine components. Thermal stability refers to the ability of the fuel to be used in a system without degradation. Thermal stress results in fuel breakdown that can cause carbon build-up on engine nozzles, afterburner spray assemblies, and manifolds. In some instances, fuel degradation changes the spray pattern in the combustor or afterburner, which leads to damage of engine components, flameouts, and augmentor anomalies.

