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Jim McFarland

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Combustion Patterns:
The Telltale Signs of Power...or the Lack Thereof

Editor's Note: The reading of post-burn residue on combustion surfaces (pistons, valves and chambers) can reveal much about why a given engine performs as it does. This lecture is directed to understanding some of the results that are described by "reading" such patterns. It includes comments about various engine components or characteristics that affect combustion efficiency…in the burn space. Some of the following discussion includes portions of previously discussed material, primarily as a platform for new information that will expand upon the overall combustion process.

BASIC INFORMATION

The mixing of air and fuel - Since air and fuel must be mixed in order to support combustion, the manner and extent to which this blending is accomplished relates to combustion efficiency. As the so-called "oxidation reduction reaction" process begins (the reduction of air and fuel to heat), the time required to accomplish this process is keyed to fuel droplet size. For example, the larger the droplet, the longer the time required for it to "burn." Conversely, the smaller the droplet the less time is needed.

We know that in a given sample of mixed air and fuel, there are variations in droplet size. If we measure this mixing based on the need for having all droplets the same size (for uniform burning rate), then the term "atomization efficiency" becomes noteworthy. Mixtures that contain a wide variation in droplet size tend to burn at irregular rates, the smaller droplets being consumed faster than the larger ones. This unevenness creates problems determining specific spark ignition timing and proper fuel volume supplied.

> **"Since air and fuel must be mixed in order to support combustion, the manner and extent to which this blending is accomplished relates to combustion efficiency."**

What's important to remember is that atomization efficiency often reflects in the residue left on piston crowns and combustion chambers. And in some instances, these patterns can also be detected on spark plug housings by the use of magnification. Just because air and fuel are mixed efficiently at the point they enter an intake manifold, it does not necessarily follow that efficient mixing will find its way into the combustion space. Directional and pressure changes from the mixing point (even if in the combustion chamber itself) to the end of combustion can negatively affect combustion efficiency and power.

What the patterns can mean - Generally, black or dark combustion residue (even if it's oily) tends to suggest a fuel-rich mixture. As the mixture trends more toward a fuel-lean ratio, the dark color begins to lighten into a tan or light gray shade. An absence of color usually suggests a correspondingly absence of any combustion at all…at least near the surface that's clean.

There is also an opportunity examine the direction of flame travel (or "mixture motion") by studying residue patterns. Plus, the detrimental effects of piston crown shapes (protrusions often used to increase mechanical compression ratio) can be noted by observing combustion residue locations.

Identifying "Good" and "Bad" Patterns

The purpose of this discussion is to focus on patterns that relate to the production of power. Those that pertain to problems such as coolant intrusion into the combustion space, blown cylinder head gaskets or conditions that also reduce power or cause damage. The "good" and "bad" patterns about which we're speaking point to inconsistent, inadequate or improper combustion efficiency… the results from which tend to reduce the amount of power available.

It is not always necessary for the entire combustion surface of a piston to be covered with residue.

In this image, mixture motion is counterclockwise. Note separation of air and fuel as the mixture passes across the sharp edge of the intake valve pocket. Radiusing in this area would help reduce mechanical separation.

Of course, if this residue is oily, there are likely problems that have little or nothing to do with combustion… other than the fact the intrusion of oil tends to create combustion efficiency problems.

In some cases, depending upon specific mixture motion, how the combustion flame is traversing the combustion space, and how much "quench" is taking place (areas where the flame is being prematurely extinguished), small patches of combustion residue or clean areas are acceptable.

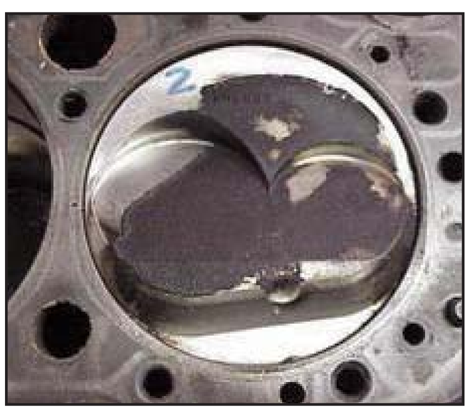
ADVANCED INFORMATION

Putting flame rates into perspective- There are numerous analogies that can be used to describe combustion flame activity. If we assume a uniform rate of combustion (flame travel) once the burn begins, then you might compare the process to touching a lighted match to the corner of a piece of paper. For air/fuel mixtures to burn in a similarly uniform fashion (or rate), they must be of uniform ratio throughout the burn space. However, in reality, this is often not the case. Visualize that the piece of burning paper has a few spots on it; some of these being oil and others liquid gasoline. As the flame reaches each of these conditions, the material being burned is not the same as dry paper and flame rate changes… perhaps slower, possibly faster.

In the case of air/fuel mixtures being burned in the combustion space, variations in air/fuel ratios within this space can cause similar changes in the rate of flame travel. Correspondingly, combustion pressure applied to a piston crown will vary, netting {perhaps} less power than might be obtained from a more uniform rate of combustion. Such problems as pre-ignition and detonation can also occur from inconsistent or uncontrolled flame rates. As you visualize all this in an engine's combustion space, think of it occurring in very slow motion. Hopefully, these processes being described will be easier to understand. Combustion, properly produced, is a process not an event.

Evidence of common flame propagation problems

Perhaps one of the most common problems result from flame movement over or past sharp edges in the combustion space. These can include valve notches or clearance "eyebrows" in the crown, sharp corners on piston domes or other abrupt changes in surface direction or finish. Not to be confused with intentional surface conditions like dimples intended to aid mixture quality, sharp edges can create unwanted eddies or vortices which may cause fuel and air to mechanically separate. Evidence of this condition, in terms of combustion patterns, is the absence of color or existence of "clean" areas on piston crowns or combustion chambers…not associated with quench areas.



This piston is in trouble. Note mechanical separation of air and fuel across intake valve relief and on backside of piston crown from one side to the other. Heavy buildup of carbon on top of piston crown indicates excessively rich mixture burn in this area. Mixture motion is counterclockwise.

Here's clockwise pattern clearly revealing mechanical air/fuel separation across the intake valve pocket, behind the compression dome and over the quench area (deck). Wide ranges of air/fuel ratios were present, including very wide areas across the dome's crown and especially inside the exhaust valve notch. From this photo alone, it should be evident how "ranges" of air/fuel mixture can exist in a given combustion space undesirably so, too.

When this condition is created, fuel is not maintained in suspension with air, typically resulting in mixtures unable to combust. One area where "clean" spots occur is on line-of-sight paths from intake port entry to the combustion chamber wall. An example of this can be found in most small-block Chevrolet V8 cylinder heads where the "back wall" of the combustion chamber is clean as viewed by looking through the intake port toward the chamber (valve removed). In fact, it is this area where benefits often result from dimples placed on this portion of the combustion chamber (see accompanying photos).

Other evidence of undesirable combustion patterns is dark (rich) areas on piston crowns and chamber walls, just past points of air/fuel separation. Examples of such areas

In this clockwise motion pattern, note the "clean" area on the chamber's back all, indicating air/fuel impingement and subsequent separated fuel from the air. The low-pressure area just past the spark plug encourages fuel to collect, leading to a fuel rich condition, as evidenced by the dark area. Separated fuel further "washes" past the exhaust valve, burning to a rich condition past this valve and toward the intake valve.

As an extreme case, this pattern reveals several unwanted conditions, including a rich condition of burn that continues into the valve overlap period, as noted by the residue between both valves. Note "clean" back wall of this chamber, a further indication of poor mixture ratios throughout the combustion space.

Here's another example of a fuel rich burn condition during overlap – to be avoided if possible. High exhaust gas temperatures and a reduced response to spark ignition timing changes characterize and engine in this condition.

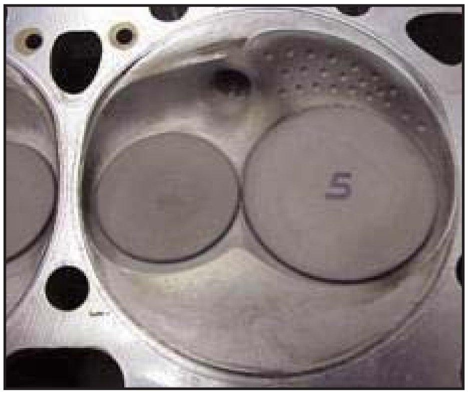
include valve clearance notches, protruded spark plug tips (or those recessed too far into their respective holes, sharp-edged chamber walls and improperly shaped piston crowns.

It's also possible to see evidence of wide spread air/fuel ratios (within the combustion space) from improper airflow quality, the result of flow patterns in or around the valve pocket…especially at high valve lifts. Dye sprayed briefly into ports during air bench analysis can reveal areas of fuel collection (separation) and distribution; patterns frequently similar to those seen after combustion patterns are established by running the engine.

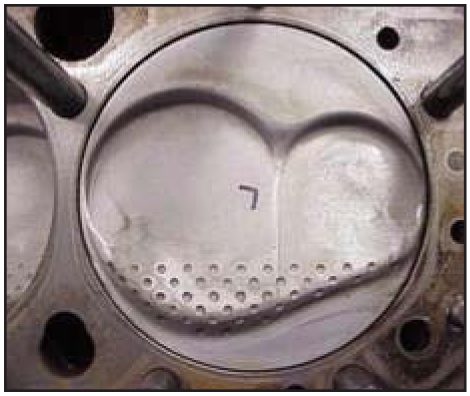
Not to be excluded from "pattern reading" are those created along the intake port path. Generally, dark areas in intake ports are stains produced by excessive reversion (exhaust gas). If intake ports become colored thusly (even the bases of carburetors can show these deposits), they signal the presence of an abundance of exhaust gas residing in the cylinder during early intake valve opening…not properly removed during the exhaust cycle. The influence of backpressure is not confined to an engine's exhaust system. Clearly, it can upset combustion efficiency, if allow to become sufficiently significant.

Major Parts that Can Adversely Affect the Combustion Process

While some of the following parts can benefit combustion efficiency; they can be equally damaging, if not properly configured.



This is an alcohol-fuel small-block Chevrolet V8 combustion chamber showing uniform combustion flame patterns, aided by the dimpled places on the back wall in an area typically "washed" with fuel.



To aid mixture quality {reduce air/fuel separation} just past piston dome edges, dimples can be placed to assist mixtures in turning over the pad and around toward the exhaust valve (counterclockwise mixture motion direction shown).

Intake Manifold Design

As pointed out in the interview with Dennis Wells (Wells Racing Engines) at the conclusion of this lecture, intake manifold design can have a material effect on the combustion process and combustion patterns relating thereto. This includes both single- and dualplane manifolds.

More specifically, any intake manifold employing a plenum chamber is subject to mixture quality and, therefore, combustion efficiency disruption.

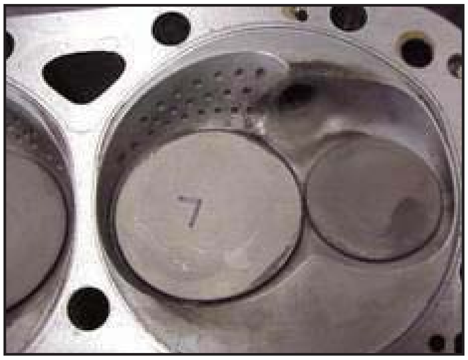
How air is "structured" in the intake runners relates to airflow "quality," a term previously discussed in these lectures. Uneven or unequal pressure distribution patterns can cause equally disrupted mixture ratios, leading to extremes in ratio range within the combustion space. Evidence of this problem can be seen from the reading of combustion patterns, discussed elsewhere in this lecture.

In addition, since reverse flow ("reversion," pressure excursions or pulses) is caused during early intake valve opening when cylinder pressure is momentarily higher than inlet path pressure, some degree of so-called "cross talk" exists among cylinders sharing a common plenum. This condition, strongly influenced by exhaust backpressure and/or valve timing, cannot only produce exhaust gas combined with fresh air/fuel mixtures (during any given inlet cycle) but also disrupt net airflow to the affected cylinder. Knowledgeable intake manifold designers take these issues into consideration whey laying out a specific design.

Piston Crowns

Recent trends toward smaller and smaller combustion chambers has enabled the use of pistons with little or no crown protruding into the cylinder head. Generally, this tends to improve flame travel efficiency, allow for more control of mixture motion (particularly swirl and tumble) and provide opportunity for increased cylinder pressure without encouraging detonation.

However, in cases where combustion chamber volume cannot (for whatever reasons) be significantly reduced, some amount of piston crown (dome) material may be required to achieve the desired mechanical compression ratio. In such instances, care should be taken to ensure this material does not impede flame travel or reduce combustion efficiency. Even prior to running a given engine package, considering the direction of mixture (or air) entering the combustion space, visualizing the relationship between the combustion roof (chamber) and floor (piston crown), and making some determinations about how crown material may affect flame travel can



This combustion chamber wall has been “laid back” in an effort to increase intake airflow. The sharp edge just ahead of the spark plug pocket (clockwise direction of mixture motion shown) creates “edge effect” and causes fuel to collect in the area of the spark plug. This fuel rich condition near the spark plug tends to delay ignition, creating a need for increased spark timing. This is not a good condition, considering the fact that earlier spark tends to increase negative torque on the crankshaft.

be of benefit. Of course, once an engine is run, physical observation of combustion patterns can reveal where additional crown material may require modification. Keep in mind that it's entirely possible to reduce mechanical compression ratio and improve flame movement, thereby gaining combustion efficiency and power.

On a personal basis, this writer has seen numerous engines experiencing flame travel problems, be subjected to piston crown modifications that reduce mechanical compression ratio on the order of 0.5-0.75 points and gain power through improved combustion efficiency. If, during flame

In this clockwise motion pattern, note the absence of a “clean” area in the intake valve relief. Radiusing this edge helps reduce the “edge” effect and cause of separated air and fuel in this area.

Look closely at this image and you’ll note the slightly darker area from about 3:00 o’clock to 6:00 o’clock (counterclockwise mixture motion direction). This suggests additional dimples should be placed in the area of the intake valve’s relief, aiding mixture quality of air and fuel passing over the crown and passing the piston’s deck surface below (as seen in this view) the exhaust valve relief.

movement, piston crown material "shuts the door" to uniform and continuous travel, power is likely to suffer. As previously suggested, make an attempt to visualize flame travel in very slow motion, in order to gain a sense for how all this works.

Combustion Chambers

As stated, this is the combustion space's roof. It must come into gas-dynamic compatibility with the floor (piston crown) as the two approach each other. Care should be taken to not compromise good flame travel with increased raw airflow, often the result of "laying back" combustion chamber walls. In fact, it's entirely possible to modify combustion chambers to increase raw airflow and net a loss in power as a result of damaged mixture quality… either by separated air and fuel, increasing the range of mixture ratios within the combustion space, or both.

SOME SUMMARY THOUGHTS

Learning to "read" combustion patterns is akin to following someone's footprints in damp sand. One interpreter might simply gain knowledge about a person having walked in a

This image indicates close piston-tohead proximity in the quench area (lower left-hand portion of the photo) and a slightly richer condition (compared to the remainder of the chamber’s color) along the edges of this quench condition – not uncommon nor necessarily undesirable when running very tight deck clearances.

certain direction. Another might not only provide this information but also approximate the person's weight, gender and type of shoes worn. Determining causes for certain combustion patterns and being able to identify areas for adjustment requires experience.

If you speak with engine builders bolting together parts. Such was the case with Dennis Wells. With more than two decades of engine building and tuning experience and a keen awareness that combustion patterns are the “footprints” to making power, he decided to begin specific study of their causes.

In the span of a few months and after sorting though numerous dyno sheets and looking at used parts, he began to unravel the marvels of what combustion patterns can reveal. His first attempt applying what he’d learned produced dramatic results…to an engine package he’d already “optimized” for an entire racing season.

There is no question about the benefits of learning what combustion patterns can reveal. Time spent matching engine characteristics with the residue left on combustion surfaces can be a valuable addition to just about any engine builder’s skill set. Just ask Dennis (we did!).

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"Performance Professor" Interview - with industry notables

Dennis Wells: Wells Racing Engines

Editor's Note: Dennis Wells is well known to the visitors of N2performance.com. His background includes more than two decades of building high performance and racing engines. In recent conversations about his experience in reading combustion patterns, several points of interest to the visitors of this site were discussed. Highlights from those conversations follow.

JMF: In your experience, have you found value in trying to correlate combustion patterns on pistons and chambers with overall engine performance?

Wells: "Yes. In fact, we're finding out that there are some specific relationships between measured power or performance and what we see in the combustion space."

JMF: Can you be more exact? In fact, how about an example of what you're talking about?

Wells: "OK. We were recently having trouble making what I thought was adequate power from an alcohol smallblock Chevy. The pistons being used were flattop. On the premise more mechanical compression was needed, we raised it about 1.5 points. While there was an increase in power, as you'd expect, the engine still seemed to lack power at high rpm. Upon removal of the heads and inspection of the combustion patterns, here's what we found.

"Even though the piston crowns showed a bit more color, it looked like something might have been limiting air flow at the higher rpm. It appeared that the additional piston material required for the compression increase was shutting off flow during the overlap period, even though the engine seemed to have more low rpm torque.

"Additional coverage of the piston crown, due we suspected from increased mixture motion from the higher compression, suggested the engine had more power potential, but crown material was obstructing net air flow at high rpm."

JMF: As a rule, what do you look for when trying to determine the combustion conditions in an engine?

Wells: "Actually, we look for several things. Clean areas usually indicate 'fuel wash' or areas where air and fuel are mechanically separating. Obviously, since you're trying to develop and maintain good air/fuel mixtures, this is a condition that takes away from optimizing power.

"We also look for ranges of color, even in alcohol-fueled engines. Generally, the darker the area, the richer the burn. As color tends to become lighter, mixtures are progressing to a leaner burn. Dark areas also signal slower burn rates than lighter ones. It can also be beneficial to have as much of the burn as possible located near the exhaust side of the combustion space. In fact, it can be helpful to configure piston crowns to encourage flame travel toward the exhaust side."

JMF: Have you found that combustion patterns tend to be different between carbureted engines and those using individual runner fuel injection?

Wells: "They can be vastly different. In common plenum intake manifolds, you find there is typically a considerable amount of 'cross-talk' or pressure pulsations that are shared among the manifold's runners. These pulses can affect not only net airflow into the cylinders but create problems in mixture quality within the combustion space.

"Problems of this type are not as prevalent in individual runner FI engines. In these cases, fuel injector nozzle spray characteristics, nozzle location in the runner and injector aiming become critical to optimizing combustion efficiency.

"When all is said and done, the quality of air/fuel mixtures in the combustion space both before and during combustion is key to maximizing power. Reading combustion patterns can be a powerful tool in determining the desired shapes of piston crowns and combustion chambers, especially when you're dealing with combustion chamber volumes that require protruding piston crown material. The patterns can tell you a lot about the operational relationship between the combustion 'floor' {pistons} and 'roof' {combustion chamber}. And in the final analysis, each can have an impact on overall combustion efficiency and power."