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The Performance Professor

Jim McFarland

The Combustion Process of an Internal Combustion Engine

Introduction

An efficient conversion of fuel into heat is a simplified objective of internal combustion engines. The complexity of this process can be reduced to certain fundamentals, essential to the understanding of or modification to a stock powerplant.

The Combustion Process (Basic Information)

In common terms, an internal combustion engine "burns" air and fuel. While there is a specific chemical reaction process that occurs during this so-called "burn," that discussion will be held for this lesson's Advanced segment.

Essentially, fuel and air become mixed during the pre-combustion process. Once mixed, this blend is compressed to a pressure much higher than atmospheric and then ignited. Ignition can be either by electrical spark or the result of "compression ignition" or "self ignition" by the admission of a diesel fuel into a high compression, air-heated environment.

If gasoline is the subject fuel, spark ignition occurs and a flame begins to travel through the combustion space. This burning action creates increased pressure within the cylinder, resulting in work (forces) acting on the pistons and forcing them downward. Such piston movement creates rotational forces (torque) on the crankshaft, culminating motive power for the vehicle. Ideally, maximum cylinder pressure is developed immediately after the piston's TDC (top dead center) position during the power stroke (acting under combustion pressure).

As "suspended" (or mixed) with air, visualize fuel droplets as small beads or spheres. The combustion process, essentially, begins on the outer portions of these droplets and proceeds inward until the droplet is consumed by the burn.

Gasoline fueled engines

In sequence, the combustion process involves the introduction of air and fuel into the cylinder, compression of this mixture to a level of increased pressure and temperature and then ignited by a timed electrical spark shortly before the piston reaches top dead center. Upon ignition, the flame travels throughout the combustion space and is only partially complete when the piston passes through TDC. At TDC, a condition called "constant volume combustion" occurs, causing both combustion temperature and pressure to increase quickly.

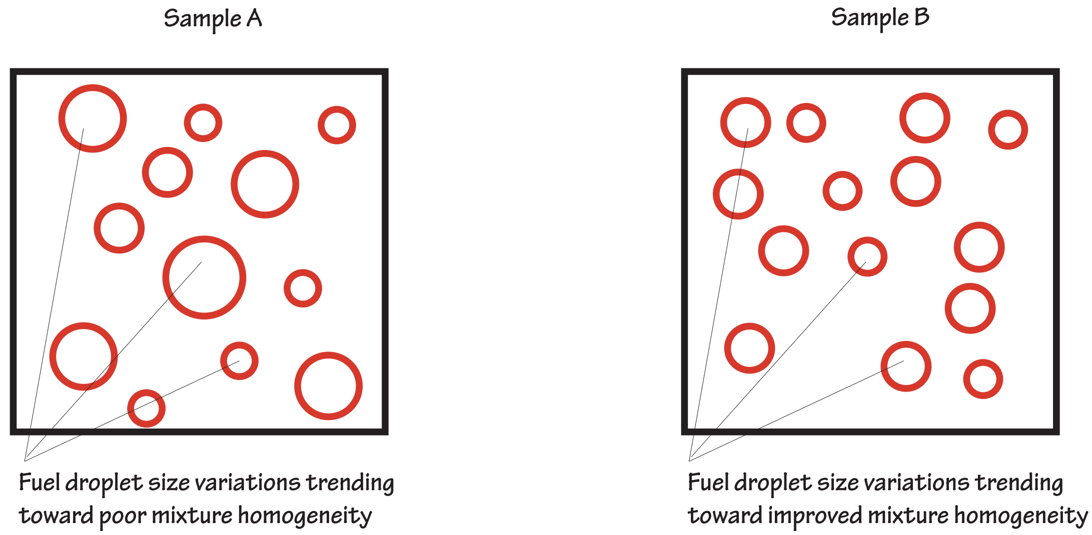
Because of differences between mechanical positioning of the piston and flame speed, peak cylinder pressure is developed just past TDC. This fact is evident in internal combustion engine study involving Engine Cycle Analysis, a subject to be discussed further in the Advanced section of this lesson. What is important about this notion is that peak cylinder pressure and mechanical TDC of a piston do not occur simultaneously. When these discussions begin to include the building and component matching for high performance or racing engines, piston position and spark timing will be revisited.

The importance of air/fuel ratios

As "suspended" (or mixed) with air, visualize fuel droplets as small beads or spheres. The combustion process, essentially, begins on the outer portions of these droplets and proceeds inward until the droplet is consumed by the burn. Large droplets require more time to be consumed than smaller

Comparison of Air/Fuel Mixture Homogeneity

Illustration 1



Note: Large fuel droplets tend to "combust" at a slower rate than smaller droplets, causing larger droplets to burn more to a rich air/fuel ratio and smaller ones to a leaner ration. Stated another way, large/rich droplets require longer time to combust than small/lean droplets.
A wide variation in droplet size poses problems for optimum ignition sprak settings, based on the fact the flame tends to speed up or slow down as a function of particle size. The result is lean portions of the mixture tend toward detonation when spark is set for slower burning large/rich droplets/mixtures.

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ones. Consider that mixtures comprised of small droplets will combust in a shorter period of time than blends of larger droplets. In a given period of time it can be assumed that combustion efficiency (completeness of burn) will increase as droplet size decreases. This is a concept to which we will return momentarily.

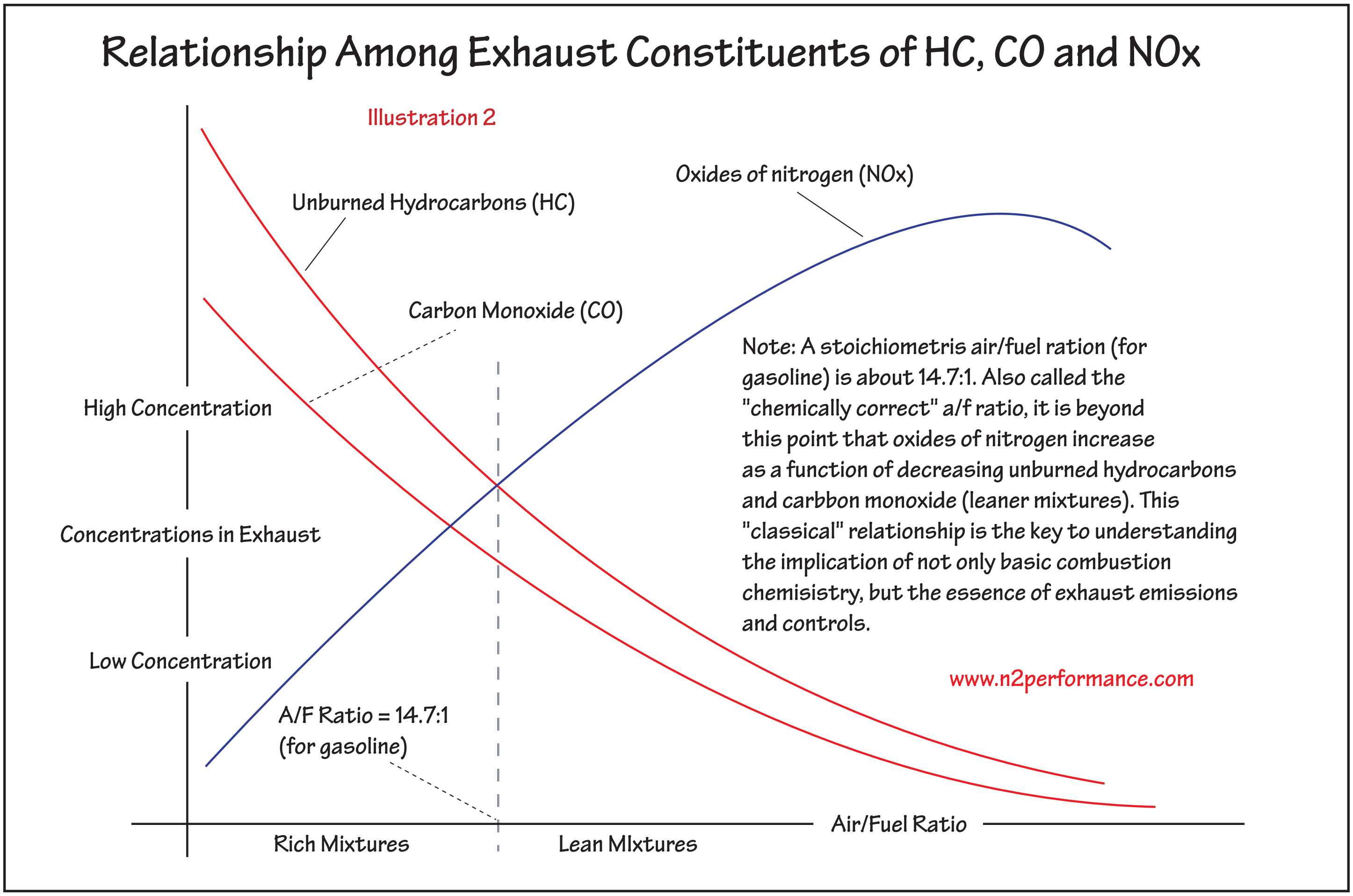
Now assume that we have a specific volume of air to which we add atomized fuel. The greater the amount of fuel added, the higher the ratio of fuel to air. Stated another way, if our selected air volume contains 1 part of fuel and 10 parts of air, we can say the fuel/air ratio is 1:10. By convention, and sometime leading to confusion, is the fact mixtures of fuel and air are often called “air/fuel” ratios, causing our example to read 10:1. Typically, the larger number denotes air and the smaller fuel, regardless of the order presented.

A stoichiometric air/fuel ratio (in the range of 14.5-14.7:1 for gasoline) is mixture termed “chemically correct” or one that suggests all of the components will be consumed during combustion. But this is under certain conditions that include constant engine rpm and load. It is also at or near the ratio which most on-board spark and fuel management systems operate during “closed-loop” functions. The problem is that engines are required to deliver power in a wide variety of road load power situations, so variations in air/fuel ratios are necessary.

For best power, air/fuel ratios on the order of 8.0-9.5:1 are not uncommon. Of course, fuel economy and exhaust emissions tend to suffer accordingly. During conditions of highway cruise or deceleration, ratios can change into the range of 15.0-18.0:1...sometimes leaner, depending upon circumstances and calibrations.

Fuel droplet size vs. flame speed

We previously spoke briefly about droplet size and its effects on rate of combustion. Recall that small droplets tend to burn more quickly than larger ones...or at least require less time to combust. It is also important that a given mixture be comprised of droplets of uniform size, or at least insofar as possible. Dissimilarly sized droplets in a given mixture tend to cause erratic flame speed; rapid with the small droplets and slower with the larger ones.



Here's the point. If combustion is initiated before a piston reaches TDC on its compression stroke, we would like to minimize the amount of combustion pressure against this upward movement. By creating a mixture of sufficiently small droplets, we can delay the point of ignition and reduce the amount of "negative torque" produced before a piston reaches TDC. A rule of thumb? Fast burn (combustion) processes enable spark timing that is nearer TDC, resulting in less negative torque and more net power delivered by the crankshaft. (Actually, this point could have been included in the Advanced segment, but you got the benefit of it here.)

Combustion problems

There are three common conditions attendant to improper combustion: {1} pre-ignition, {2} detonation and {3} after-run.

Pre-ignition is exactly what its name implies: ignition that occurs before it is intended. It can be caused by hot spots in the combustion space (glowing bits of carbon, sharp edges of valves, etc.) and is often accompanied by a "pinging" sound, especially during acceleration or conditions of load. It can also be caused by poor fuel quality or insufficient octane. Pre-ignition seldom causes parts damage but is typically characterized by a loss in power.

Detonation can cause damage, and it is often severe (broken pistons, rings, cracked cylinder heads or failed head gaskets). The sound of detonation, generally during acceleration or load is "knock," the result of sudden and extremely high cylinder pressure, much like a hammer blow against affected engine parts. At the risk of over-simplification, detonation is caused by sudden and uncontrolled combustion of the unburned portion of an air/fuel mixture. Prolonged pre-ignition can lead to detonation, but they are not the same phenomena.

What's the rule of thumb that defines pre-ignition and detonation? Pre-ignition occurs before the combustion process is designed to begin. Detonation is a condition that occurs after combustion begins.

After-run (sometimes called "dieseling") occurs after the ignition key is switched off. Causes vary, but the more common ones are poor quality fuel, an overheated engine or excessive idle rpm. Basically, the fuel self-ignites, much like a diesel. After-run is characterized by erratic running, a "rattling" sound and occasionally with attending knocking. Spark plugs with a high heat range can also lead to after-run.

Some afterthoughts

Remember, the burning of air and fuel in an engine is a process, not an event. Proper combustion requires time, should begin smoothly and continue throughout the process, uninterrupted. If it does not, the delivery of optimum cylinder pressure will not be converted into useful crankshaft torque. It is desirable to create mixtures consisting of small fuel droplets, uniform in size. Mixtures of this nature (quality) enable reduction in initial spark timing, leading to reduced negative torque and higher net power.

The Combustion Process (Advanced Information)

Engine Cycle Analysis

It is within the combustion space that much can be learned about an engine's output, whether it is efficient or not. Of the current methods that enable such study, Engine Cycle Analysis (ECA) is gaining in popularity, use and affordability. By the use of high-resolution, rapid-response pressure transducers mounted and exposed to combustion pressure, real-time in-cylinder pressure measurements can be made and correlated to crankshaft positions. By the manipulation of certain mathematical equations of thermodynamics, a variety of combustion-related data can be produced from the basic pressure/crank-angle information gathered with ECA. (A sample trace of cylinder pressure vs. crankshaft angle is provided with this lesson.)

ECA also enables examination of various combustion space temperature histories, including the points of intake valve closing, exhaust valve opening and peak (maximum) combustion temperature. Also in the data mix are percentages of air/fuel charge burn, length of the burn, ignition delay and the time required for fully developed combustion. The category that encompasses these data is the "mass-burned fraction vs. crankshaft angle" information assembly. As you will note in the "pressure vs. crankshaft angle" plot, peak cylinder pressure occurs just past TDC piston position. This phenomenon is particularly interesting when considering the fact engine timing lights reference mechanical TDC and not peak cylinder pressure.

Even though ECA evolved largely from the academic community, it is gaining popularity and frequency of use with both OEM and motorsports teams. Original Equipment Manufacturers are finding the value of ECA enhances ability to design engines, parts and systems that meet increasingly stringent exhaust emissions levels and fuel economy standards mandated by the United States Environmental Protection Agency. Race teams and engine builders are discovering the precision and insights provided by ECA, especially with respect to optimizing power "one cylinder at a time." It is predictable that ECA will become in broader use as internal combustion engine designers and modifiers learn how to optimize its benefits.

Combustion flame travel
(and factors that influence its behavior)

It was stated earlier that the internal combustion engine's combustion process is not an "explosion" of fuel and air. Rather, ignition occurs and the resulting "flame" it creates is intended to spread evenly throughout the available combustion space.

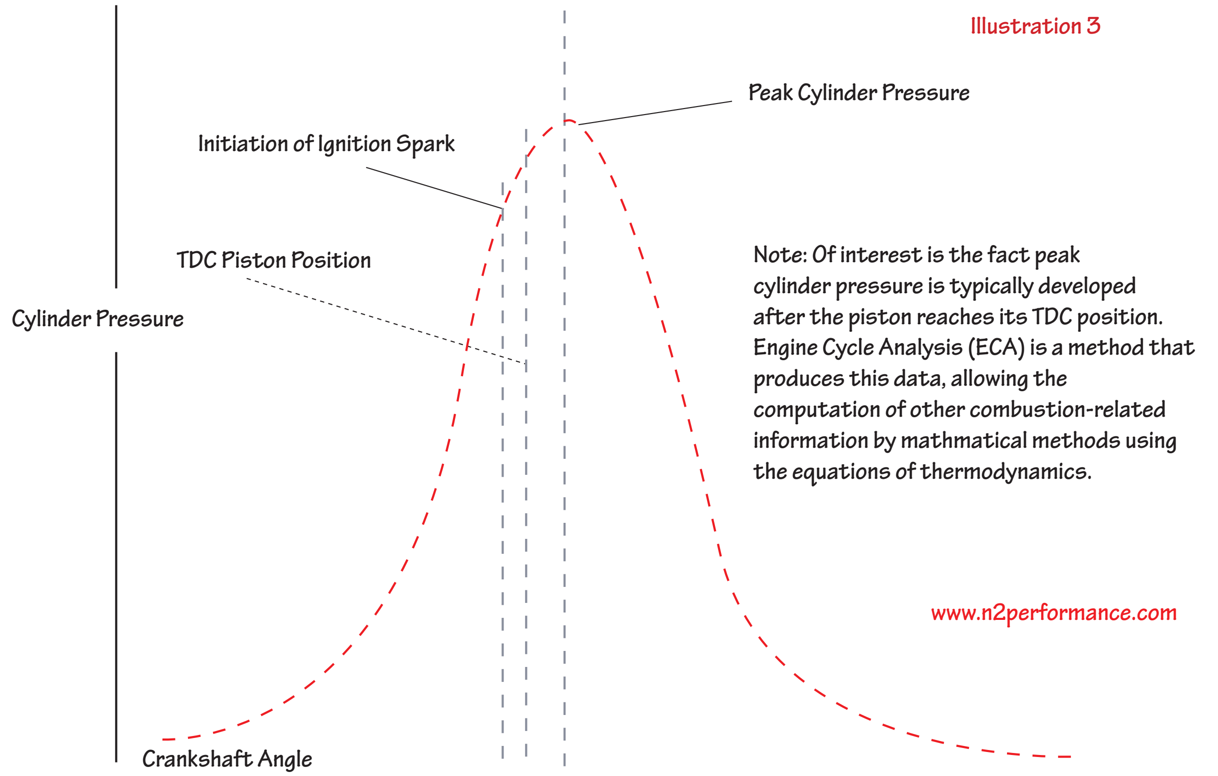
There was also prior discussion about the conditions of and results from abnormal combustion (pre-ignition, detonation and after-run). Keep in mind that the crankshaft is turning throughout the complete period of flame travel, sometimes as much as 35-45 degrees of rotation.

Because of the functional time differences between piston movement and flame rate, it is not possible to ignite fuel mixtures at TDC piston position and complete the burn instantaneously. Some "lead time" must be provided to accommodate these differences, requiring that ignition be initiated some time before TDC. At TDC, a phenomenon is produced called "constant volume combustion." It is during this instant that both pressure and temperature rise sharply, leading to abnormal combustion (particularly detonation) if contributing conditions exist.

Ideally, work {pressure or torque} done by a piston on the

Relationship Between Cylinder Pressure and Spark Ignition Timing

(As a function of crankshaft angle and piston position)



expanding combustion gases, peak cylinder pressure occurring somewhat past TDC and because combustion space (volume) is greater at peak pressure than at TDC, peak pressure will be less than it COULD have been at TDC. An important component of this sequence is how the point of ignition is determined absent the ability to correlate spark timing with peak pressure.

Over time, engine tuners have discovered that so-called "power tuning" is a method that approaches compensation between ignition point and in-cylinder pressure development. Typically, external timing references {marks} are used to set initial timing with final adjustments made by evaluating engine performance under acceleration or load. Reduced engine performance, spark "knock" or both can be used as the limiting point for final spark timing settings. This method can also be used to compensate for variations in fuel quality or octane.

It should also be considered that premature initiation of ignition spark can be counterproductive to net torque. To minimize net pressure losses between compression and expansion (power) strokes, excessive spark timing should be avoided. Consider the sequence of events embodying cylinder pressure development before and after TDC piston position, during the compression and expansion strokes.

Cylinder pressure and temperature begin to increase as the piston ascends. Both temperature and pressure increase sharply when ignition occurs. The amount of pressure against which the piston must act can be termed "negative torque" and subtracts from the amount of "positive torque" produced once the piston passes through TDC.

Based upon engine design or ignition conditions, the amount of time (or crankshaft degrees) necessary for the combustion flame to traverse the combustion volume (space) can vary. This condit ion relates to the issues of "fast" or "slow" burn engines. What is important is that the faster a flame is propagated, the less time is required to complete the burn. This translates into the initiation of spark timing that can be delayed closer to TDC piston position. The later the spark, the less negative torque will be applied to the crankshaft, resulting in a higher "net" torque. Simplistically, Indicated Mean Effective Pressure(IMEP) is an indication of this net or difference between negative and positive torque. In reality, it is the amount of net work available to turn the crankshaft in a positive direction.

Interestingly, as flame speed is increased and spark timing delayed, there can be a net gain in torque with no other changes to engine volumetric efficiency or airflow. To this end, there are some elements worthwhile discussing that will maximize IMEP.

Engine variables that can affect flame rate

Mechanical compression ratio:
Raising mechanical compression ratio can increase Air/fuel mixture density. The denser a mixture, the faster the flame rate. As flame speed increases, ignition timing can be reduced, typically resulting in higher IMEP.

Piston displacement:
As a rule, larger engines require more time for the combustion flame to traverse the combustion space. Therefore, it takes longer to complete the burn than with smaller engines. If the ratio of piston area to effective inlet valve area is the same, flame rate (including mixture flow rate and turbulence) tend to be about the same. Almost independent of engine size, flame rate includes a function of mixture homogeneity or the ability to produce air/fuel blends of small and relatively uniform droplet size.

Intake pressure:
Whenever an engine's throttle is opened (or is supercharged), pressure in the intake track increases, thereby causing an attending increase in mixture density in the combustion space. As a rule, supercharged engines have relatively high flame rates and, correspondingly, require less spark advance than those normally-aspirated.

Engine speed:
An understanding of piston speed is necessary to grasp the relationship between engine speed (rpm) and flame rate. By conventional means, the calculation of piston speed produces an "average" value, determined by 2 x piston stroke x rpm. Considering the piston area (upper portion), piston valve one can make an approximate calculation of inlet air. As inlet air velocity increases, so does the proportionate amount of turbulence or "mixture motion." This motion tends to increase flame rate by an increase in the difference between burning and unburned portions of the air/fuel mixture. By the inducement of mixture motion, particularly controlled mixture motion (swirl and/or tumble), flame speed can be increased by a factor of as much as 20:1…mixture motion vs. the absence of particular mixture motion.

Even in high performance and racing engines, piston speed may increase more rapidly than the rate of combustion. A measure of compensation for this difference is offered by advancing ignition timing, but the tradeoff is in how this negatively affects IMEP. Current methods of inducing mixture motion are reducing the reliance upon early ignition timing, particularly given the opportunity to position fuel injectors and shape combustion spaces in a fashion that accelerates the burn rate.

Air/fuel mixture ratio:
As a rule, air-rich (lean) mixtures burn more quickly than fuel-rich (rich) mixtures. Depending upon the degree of "leanness" or "richness," combustion flame temperature can range from high to low. For example, rich mixtures tend to burn cooler than lean mixtures, although it is possible for lean mixtures to burn toward cooler temperatures as fuel is removed from the process. Best power mixture ratios are generally in the "slightly rich" range, tending to show the highest flame temperatures and rates of burn.

It should be noted that within a given combustion space, air/fuel ratios may not be uniform. This relates to the issue of mixture homogeneity and the desirability of uniform mixtures {with uniform fuel particle sizes} distributed throughout the combustion space. Any condition that encourages mechanical separation of air and fuel or causes extremes in mixture ratio should be avoided. Detonation can result from improper mixture conditioning.

Exhaust gas (contamination) in the combustion space:

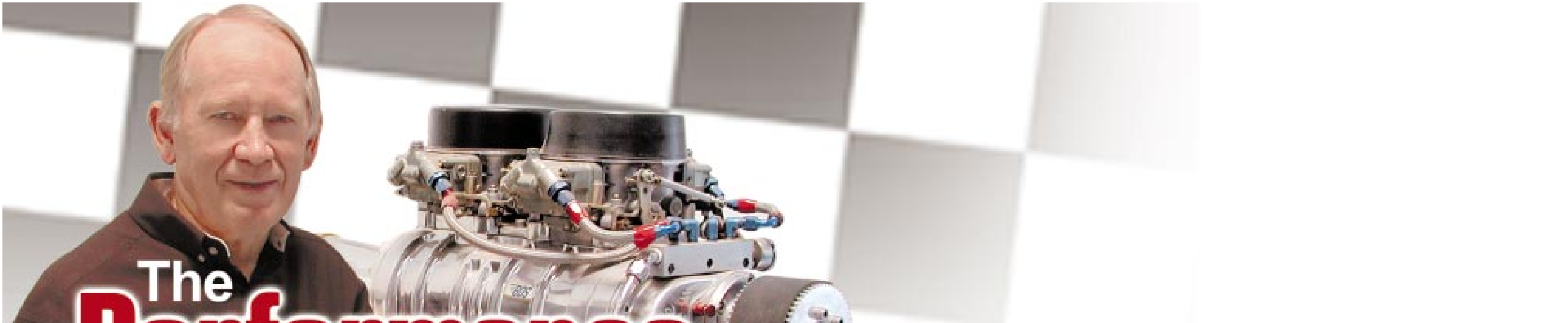
The dilution of air/fuel charges with combustion residue tends to reduce both flame rate and temperature. Residual volume is a function of an engine's blow-down efficiency or ability to rid the cylinders of combustion byproducts.

Further complicating the issue is the mixing of fresh air/fuel charges with combustion residue. This tends to create wide ranges of air/fuel ratios in the combustion space, often leading to the requirement for early spark ignition timing and lost power. Re-circulated exhaust gas (EGR) is a common method of reducing combustion temperatures, along with oxides of nitrogen (NOx), for decreased exhaust emissions. However, the method is detrimental to net power and fuel economy.

Some Afterthoughts

As these "lessons" unfold, there will be references to other combustion-related issues. Among them will be the importance of air/fuel mixture homogeneity and quality as each relates to combustion flame rate, mechanical compression ratio, ignition spark timing and IMEP or net power.

It is important to recognize and remember that it is in the combustion space that an engine's output is ultimately determined. How that space is supplied combustible mixtures, the efficiency of their burn and the skill in removing the byproducts will be core to a variety of aspects dealing with making power.



"Performance Professor" Interview - with industry notables

Zora Arkus-Duntov {deceased}

The following comments were obtained in a 1994 interview with Zora Arkus-Duntov, internationally renowned Chevrolet engineer who pioneered the availability of "ready engineered parts for high output" at the factory level, was a driving force in initial development of the Corvette and established the importance of a "performance aftermarket" during the mid-1950s. His legendary engineering background included the original Patent on Chevrolet's Rochester Fuel Injection system and multiple valve, overhead camshaft experimental big- and small-block Chevrolet engines.

"Combustion engines are a fascination of young hot rodders. Given the opportunity, they will break everything from flywheel to the driving wheels, trying to get more power. It is this fascination that has caused new car manufacturers to seek and build high performance engines. Some have done this well and others have not, just bolting on parts that are less than efficient.

"Too often, I think, hot rodders misunderstand the importance of good combustion. This is not an easy subject and, therefore, one they like to avoid. Many are not engineers, and I propose that it is easier to read the performance and hot rodder magazines to imitate what maybe has worked for someone else. This is often unfortunate because understanding why an engine makes power is the path to making more.

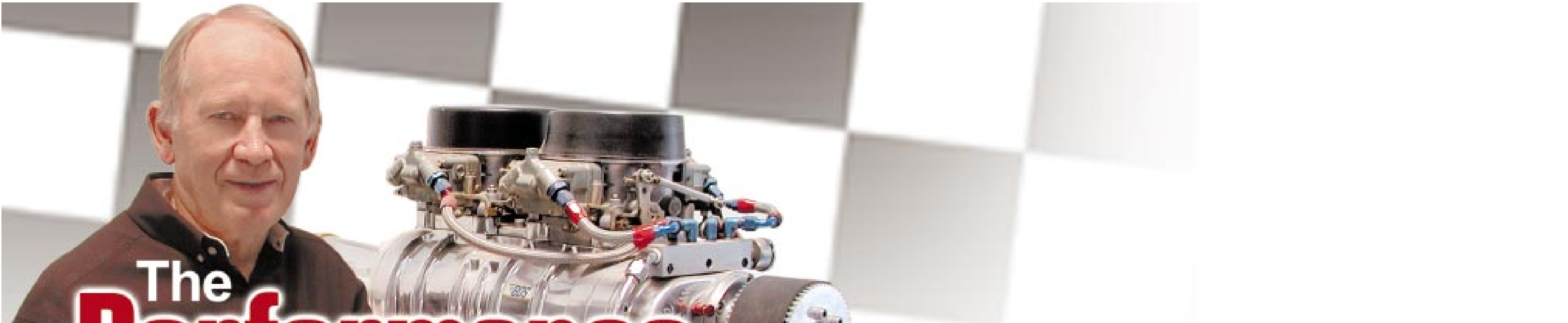
"When I did Chevrolet fuel injection for '57 Corvette, one objective was to give good fuel atomization throughout a wide range of engine speed. Carburetors, even on a good intake manifold, leaves something to be desired for delivering proper mixtures, especially at mid- and low-rpm where torque is important. Even mechanical fuel injection was better than carburetors. So we made more power than carburetors because combustion efficiency was improved. Fuel economy was also better.

"Since then, aftermarket intake manifolds and carburetors are more efficient, but they have become so because of better handling of mixtures (quality). When lead was taken from gasoline, compression ratios needed to be reduced because factories were not building engines with good combustion efficiency. Later on, like with new Chevrolet LS1 design, combustion efficiency was better and compression ratios could be increased, which they were. As a result, engines are making more power, especially at low- and mid-rpm where they must run for meeting fuel economy and emissions standards.

"I think young hot rodders do not realize the connection between good combustion efficiency and things that relate to it. Fuel economy, low emissions and power are not unrelated because of combustion efficiency importance.

"When building a high output engine, it is first necessary to decide where the rpm will be (most frequent use) and then choose parts that will make good combustion efficiency there. Sloppy parts selection will cause sloppy power output. I suggest that a good method is to read about engine building as part entertainment and part knowledge. Learn as much as possible about engine efficiency from the textbooks that don't have a bias. Then combine these two sources to make decisions about what is the best combination for making high output. Sometimes the magazine writers aren't told all the important information or cannot get it said correctly, even though they try very hard.

"I propose that the best way to build a high output engine is to be a free thinker. More important, realize that unless things are done to create good combustion efficiency, a high output engine will not meet all expectations. I learned this the hard way when I was a young hot rodder and thought I had all the answers."



Review Questions — True or False

1. Carburetors have little or no influence upon the quality of air/fuel mixtures.

2. An engine's combustion process has been completed by the time a piston passes through its TDC (top dead center) position.

3. Small fuel droplets require less t ime to combust than larger ones.

4. It is important that an engine's air/fuel mixtures be a blend of fuel droplets of uniform particle size.

5. "After-run" is a condition whereby an engine experiences combustion conditions similar to a diesel engine.

6. ECA (Engine Cycle Analysis) is a process of in-cylinder pressure measurement that leads to information about how efficiently an engine is converting fuel into heat.

7. Under normal circumstances, an engine develops peak cylinder pressure shortly after a piston passes through TDC (top dead center).

8. Detonation and pre-ignition are not the same conditions, although pre-ignition may lead to detonation

9. As an engine's mechanical compression ratio is increased, flame speed is typically reduced.

10. Combustion residue (exhaust gas) present in an engine's cylinders tends to increase the rate of flame speed.

Answers

1. **False** – The function of mixing air and fuel begins at the carburetor.

2. **False** – Mixtures tend to burn through several degrees of crankshaft motion that extends beyond TDC.

3. **True** – Simply stated, the "burning" of fuel droplets begins on the outside and progresses inward until the process is completed. Therefore, large droplets require more time than s maller ones.

4. **True** – Uniformit y allows for a more gradual and predictable rate of burn and the possibility of avoiding incomplete or uncontrolled combustion.

5. **True** – "Self ignition" is similar to the process involved with diesel engines.

6. **True** – Time-pressure traces as a function of crankshaft angle provide information processed in equations of thermodynamics to derive multiple data streams.

7. **True** – The combustion process and attending pressure rise dwell several crankshaft degrees past TDC (see illustration provided).

8. **True** – If the combustion process begins prior to a specified timing point, uncontrolled conditions (detonation) may result.

9. **False** – Among other factors, mixture density is related to flame speed. The higher the density, and all else being equal, the faster the rate of combustion.

10. **False** – This material dilutes fresh air/fuel charges, resulting in slower flame speed and reduced combustion efficiency.