Sunset Engine Development

EXHAUST GAS TEMPERATURE

There seems to be some confusion and misconceptions regarding exhaust gas temperature out there. Racers and engine people often ask us what their exhaust gas temperature should be. Some even believe this is the “holy grail” of engine tuning. Let’s examine what we need to know to determine the optimum EGT.

The EGT is the heat measured in the exhaust pipe. Commonly, this measurement is taken with a thermocouple placed in the pipe approximately one inch from the port. Type K thermocouples are typically used because they are the most linear in the range of temperature that we are concerned with. This is important if analog type meters are use. Non-linearity can be corrected for with digital meters via look-up tables programmed into the device.

This heat in the exhaust is wasted heat that was not converted into work on the piston, nor was absorbed by the cylinder wall, combustion chamber, exhaust port or exhaust pipe - yet. In other words, this is the heat left over. It serves no positive purpose unless you want to say that the hotter the exhaust gas is the more energy it has and this is a definite aid in driving the turbine wheel of a turbocharger. You could also argue that the velocity of sound will be higher in the primary pipe and this could be of some vague benefit in tuning the stationary pulse for better scavenging at some rpm. In reality we don’t purposely design a system to promote higher exhaust gas temperatures, because higher EGT means lower thermal efficiencies, which spells lower horsepower and less fuel economy.

Compression ratio has a strong influence on the exhaust gas temperature. Air constitutes the bulk of the working gas in a gasoline engine. Understanding the nature of air as it is compressed is the key to understanding why power goes up as compression ratio is increased. In accordance with Charles’ law there are two different specific heats for dry air. One when expanded at a constant pressure (.2374 but per lb) and one when expanded at a constant volume (.1689 but per lb). It is the ratio of these two specific heat values that gives us the polytropic exponent value of 1.4, known as y. You may recognize this symbol from some basic thermodynamic calculations in engine or physics books. When y is used with the compression ratio (r) in the formula $1- (1/r)^{y-1}$ we get a value know as the “air standard efficiency.” The ASE shows what percentage of the external heat (from the act of compression) added to the air is converted into work. As "r" goes up the ASE goes up which is saying thermal efficiency goes up. The higher the thermal efficiency the more of the **internal** energy (enthalpy efficiency) in the fuel is converted into work on the piston. The more heat energy converted into work the less there is left over to be wasted out the exhaust port. Hence, the higher the compression ratio the lower the exhaust gas temperature. You can thank Charles and his laws for this insight.

If what I have said is true - and it is - then raising the CR should lower the EGT. That's a fact Jack. But two engines with the same compression ratios don't necessarily have the same EGTs.

It is actually the effective or dynamic compression ratio that determines the ASE and how much internal energy can be released. This, in a nut-shell, is MEP (mean effective pressure) or cylinder pressure. Since it is cylinder pressure (combustion pressure) which determines the amount of heat which can be released, used, and therefore wasted, anything which effects cylinder pressure also effects EGT. As you can imagine there are numerous variables - some more hidden that others - that effect cylinder pressure.

These variables include volumetric efficiency (VE) which is a function of throttle position and rpm (which determines engine load), and valve timing. This "trapping efficiency" determines the amount or mass of air-fuel mixture captured in the combustion space and is called the charge density.

Charge density, to a lesser degree, is also influenced by coolant temperature, intake air temperature, absolute barometric pressure, humidity, fuel type, fuel mixture, and material of the intake manifold, cylinder head, and intake valve.

Since VE is generally highest at the torque peak this is where you would expect the highest EGT, right? Wrong. The torque peak is a point of high efficiency and that means less wasted heat. The engine does, however, gain thermal efficiency as rpm increases due to limiting cycle time and therefore limiting heat dissipation time. So, from the torque peak to the horsepower peak we may or may not see the EGT increase, assuming the A/F ratio doesn't vary. Typically we see it continue to rise, but whether this is from a decrease in thermal efficiency or the result of the exhaust port heat rejection rate due to less delta T, is hard to say.

It is not uncommon to see three to four hundred degrees difference in EGTs on an engine at part throttle conditions due to the influence of throttle angle and manifold runner differences. At WOT (wide open throttle) 250 degrees difference can be expected on manifolds and cylinder heads which do not distribute fuel as evenly as they do air. Even 150 degrees is common on fuel injection systems with independent runner manifolds and injector nozzles which have been flow matched. These discrepancies in EGT are also influenced by the dynamic influence of the exhaust system and subtle differences in cylinder to cylinder valve timing.

If the intake system flows nearly equal on the air flow bench and the injectors flow nearly equal on the fuel flow bench, then why are the temperatures so varied? The answer is that flow isn't everything.

A big variable is the combustion process itself. How the fuel is burned, or rather, how efficiently. Two intake tracts and combustion chambers with the same air and fuel flow could be different if they create different turbulence. Cylinder-to- cylinder differences in velocity, swirl and tumble affects turbulence and therefore the charge burn rate. It would seem that CNC porting would produce complete uniformity of the intake port and combustion chamber thereby eliminating it as one of the variables. However some engines, such as the big-block Chevrolet do not have identical intake ports to begin with. Half the ports have a different offset or bias so how can we expect combustion to be the same even under optimum conditions.

The manifold, intake port, piston-top and combustion chamber all combine to affect the charge motion within the cylinders. Even though you can measure tumble (whether it be positive or negative) and swirl torques on the flow-bench, changing them in a positive way is something that is not easily done. It is argued that swirl and tumble don't even exist and that tangential velocity gradients produce many vortices as the charge turns past the valve and that it is the result of many of these vortices that give us erroneous swirl velocities. I digress. Anyway, the overall shape of the combustion chamber and piston top are the main contributors to turbulence because they also affect squish, quench and therefore flame travel.

The type of fuel and the air-fuel ratio determine the overall heat, and very importantly, the heat release rate. Different fuel compounds burn and release their heat at different rates. Take Formula 1 racing for example. In the last few years one of the leading contributors to horsepower increases (as high as 17%) has been fuel. Fuel companies (Elf, Shell, AGIP, Mobil, BP) and their engineers have had their own war raging in F1 and at every battle (race) they needed something new to keep pace. This reportedly escalated fuel costs to over $1000 per gallon. These very high rpm engines need faster burning fuels which release their energy quickly. Fuels can be "brewed" to provide heat release rates as a function of the intended piston speed. Every fuel releases its energy a little differently depending on the chemicals in it. This certainly affects the spark lead requirement and, of course, the EGT.

The "latent heat of vaporization" will also vary with fuel composition. The more heat that is used in converting the atomized fuel into vapor the lower will be the intake charge temperature. The lower the charge temperature the lower the EGT. This is about a one to one ratio. Alcohol fuels, especially methanol, have very high latent heat values. EGT is a lot lower with alcohol. You should also note that the lower the ambient air temperature the lower the EGT.

Anything that causes the air-fuel mixture to change will effect EGT. Barometric conditions such as temperature, humidity, and barometric pressure affect the mass of air inducted into the cylinder.

Even variations in valve timing (not necessarily cam timing) will have a small effect on EGT. Some of the variables might include the valve events themselves, valve lash, valve-train deflection, and rocker ratios. The odds of these valve-train variables combining to provide the same valve timing in a running engine are zero.

Since engine overheating can promote detonation we must conclude that coolant temperature will affect combustion. Therefore discrepancies in coolant flow within the cylinder heads can cause combustion characteristics to change.

Certainly the exhaust system is going to have a tremendous effect on the combustion process. If exhaust tuning is, in effect, due to the precise design of the system, to create a lower pressure in the cylinder at the time of early intake valve opening, we can expect a gain in VE. It is even more enhanced if a tuned intake system can provide a positive pulse on the other side of the intake valve to create an additional kick (delta P) to the incoming air-fuel charge The exhaust system material, length and diameter all affect cylinder scavenging and therefore EGT.

Perhaps the biggest single factor influencing EGT is the air/fuel mixture. Maximum combustion heat is generated with mixtures slightly rich of stoichiometric (equivalence ratio of approximately 1.1) at the start of the expansion stroke. Maximum EGT occurs at the stoichiometric ratio. Mixtures on either side of stoichiometric will be cooler. As air/fuel ratio is varied, on the dyno, you can observe changes in EGTs. Since richer ratios are required for maximum power this is a condition we usually only observe by going richer. The rate of combustion (burn time) slows down at very rich or very lean air-fuel ratios. Heat released at lower pressures is mostly unproductive.

We have also observed, as I believe most everyone else has, that the cylinder head material has a significant influence on EGT. The heads are exposed to the highest gas pressures and temperatures, as well as a scrubbing action of the combustion process. Consequently, the cylinder head transfers, on the average, 5 to 13 times as much heat per unit area as the cylinder walls, depending on design and amount of cooling. The heat conductivity between aluminum and cast iron is 27 btu-ft/(ft x hr x F) for iron compared to 119 for aluminum. Aluminum heads seem to lower the exhaust temperature between 50 to 150 degrees under cast iron, depending on head type and other variables. This then is a major factor in the EGT picture.

There is another unfortunate engine characteristic. This condition is termed “cyclic variation” and it is common to all engines. It is a function of cycle efficiency at a particular rpm and load condition. It is the result of mis-fires per unit of time. There may be many variables working with or against each other to cause the cycle efficiency to vary. These variables cause the engine, or more commonly, a individual cylinder or cylinders to be “unhappy” (inefficient) with the particular condition that exist in the cylinder at that time. The cylinder reacts to this condition by mis-firing every so many cycles depending on its degree of unhappiness. It may mis-fire as much as every other cycle or as little as every thousand cycles, no one can say. Maybe an ECA (engine cycle analyzer) could see this. There are many conditions which could cause this by themselves. Some are obvious - like poor spark quality - but others are more hidden. Certainly cylinder scavenging is going to be a leading contributor.

Scavenging efficiency is a function of how well the cylinder rids itself of combustion residuals and prepares itself for the next intake cycle. The accumulative process of left-over “poop” at the end of the exhaust stroke will eventually builds to the point where combustion cannot be initiated. This built-in EGR is the same condition that causes poor idle quality in engines with high overlap camshafts. I recently read technical paper in which the author referred to this condition as "exhaust lockup" - a nifty term. This condition may not effect all cylinders equally. Even a small change in rpm or load may cause the cylinder to become happy again. Cyclic variation is always happening in any engine at any given time. If there are many cycles between misfires, and if it is only happening in a cylinder or two, it may not be noticeable to the ear. Again, it's always happening but you don't know it.

Sometimes we are restricted as to where we can place the thermocouple probes to measure the temperature. You would expect the longer the distance form the exhaust valve -such as a longer exhaust port itself - the more mass there would be to sink away exhaust heat. We recently did a dyno session with a turbocharged boat engine with water jacketed (therefore cooled) exhaust manifolds checking the EGT right out of the ports and then checked the EGT 12 inches downstream from there after they collected. The temperature entering the turbine just a foot from the exhaust ports was over 100 degrees hotter. We thought that this did not agree with theory. "The great tragedy of science is the slaying of a beautiful hypothesis by an ugly fact" - Thomas Huxley. After some head scratching we realized that the exhaust was being compressed - in this case 26 psi worth. So manifold pressure was causing the temperature to rise. The first thought was that this condition was nothing more that the continued burning of the mixture, but further testing proved otherwise. When things occur that we don't understand the tendency is to "force-fit" them into complying with invalid explanations.

Perhaps there were other hidden variables, I always assume there are. I also assume that very often these hidden variables tend to be negligible or cancel each other out.

Close to the ports temperatures change very rapidly. Thermocouple mass (wire size) is going to cause some finite delay between the instantaneous EGT and what the meter is showing. This time lag is further aggravated by the typical slower reacting analog meters which have a natural tendency to dampen quick movements. So, like light from a distant star, by the time you read the meter it is indicating ancient history. Digital gauges and data acquisition may not be a lot better due to slow up-date rates. This can be the cause of a hidden variable when trying to correlate data. Large thermocouple wire, next to thermistors, react the slowest and cause temperature to lag behind some of the other data.

I have talked to and read about engine builders who claim their engines produce super low EGTs (900 degrees F being typical). They say this is due to the very high thermal efficiency of their engines. They equate this to very high static and effective CRs due to high VE and great turbulence. This may be so, but we have never seen anything near this. If these reports are true one of four things may be occurring; (1) they have made a tremendous break-through (2) there are hidden variables that are influencing their data (3) they are testing differently than we are (4) they are light-years ahead of us. Perhaps the latter is the most likely.

Lets review some of the variables influencing EGT that I have mentioned. Combustion pressure is influenced by:

Volumetric efficiency - which is influenced by:

- Valve timing
- Fuel composition
- Intake system design

Exhaust system design
Engine temperature
Intake air temperature
RPM
Fuel mixture
Cylinder turbulence
Barometric pressure
Humidity
Spark timing
Coolant circulation
Where temperature is measured
Thermocouple size
Cylinder head material

As you can see there are many factors which contribute to the overall exhaust gas temperature and some of them we have no control over to any reasonable extent. I do feel differently, however, about EGT than I do BSFC (brake specific fuel consumption), in that, we can form pre-conceived opinions as to an approximate range that the temperature should fall into based on empirical data. As long as the major factors such as, fuel type, compression ratio, fuel mixture, and where the EGT is being monitored, does not stray very far from the "norm," a reasonable guess could be made about the temperature. You would probably be within 150 degrees.

Since we run most of our dyno tests on similar fuels and engine types we have learned to pay attention to the EGTs when they get "out of line" with what we expect to see. Just because the exhaust temperatures are not what we expected to get doesn't necessarily mean something is wrong with the engine. Fortunately we have other data with which we can correlate the EGT. Such as; Air/fuel ratio, BSFC, BSAC, torque per cubic inch, spark plug condition, piston top and cylinder wall condition (as observed with a boroscope), and most of all, lambda. All these pieces of information contribute to our opinion as to the well being of the engine fuel mixture wise.

On the test bed (dyno) we rely on EGT mostly for indications of catastrophic failure (screw-ups like dangling plug wires) and as a sign of detonation. Our standard procedure during a steady-state "pull" is to take the engine to various rpm points and hold it there while we gather the data. This allows things to stabilize somewhat and also gives us time to gather all the data at different time intervals - such as two seconds between button pushes - so we can average out the data. Statistically, being able to throw out the high and low values make the data more reliable. Anyway, because we now have five different sets of data taken two seconds apart at one rpm we can see some interesting trends. One thing that came from this method was observing the EGT on a single cylinder steadily dropping at these two second intervals. This is catching detonation in the act - and sometimes when the detonation detector doesn't (sensors sleeping on the job I guess). This effect doesn't show up when we do a step test or an acceleration test.

Most light aircraft use EGT gauges as a mixture indicator. As you would expect with anything aircraft there is a great deal of testing and documentation required to get anything STC approved. There is a tremendous data base on certified aircraft engines. Engine manufactures supply EGT numbers to allow the pilot to extract either maximum power for take-off or maximum economy for cruising. Avco Lycoming allows leaning to peak EGT at 75% power setting. The first time I encountered EGT was in a small airplane. It was an analog gauge and to accurately read it you had to focus on it an count the major and minor divisions to the left or right of a number to interpret the temperature. This is not a big deal in an airplane waiting for take-off or while cruising along in the wild blue yonder but I can't imagine trying to read an analog gauge in a race car.

In this situation I think racers are making a mistake by buying the old analog aircraft style EGT gauges or gauges from diesel trucks. Digital is the only way to go when you have to read the temperature with just a quick glance. Of course for racing, like the dyno, data acquisition is the best way to gather data.

Before I quit Tektronix me and another electronics nerd started a little company that manufactured digital accessories for race cars, airplanes and dynos. We had what must have been one of the first digital tire pyrometers. It recorded the temperature across the tire in the standard three locations and stored them so you could do all four tires quickly and then play back the data later. We showed it to the Goodyear engineers at a race and they politely laughed and kept using their slow moving analog antique for about another year. Now you can't get anything but a digital one. We also manufactured digital EGT stuff that I used on our race-car.

In 1979 I wrote a one page paper on the exhaust gas temperature monitoring equipment that we were manufacturing. I think I will include that page at the end of this paper. I have changed my opinion about this type of equipment since I wrote that paper but I will include it so you can see what the thinking was back then.

This is all leading to my classic example of out-smarting yourself. We ran (in a GTO Corvette the IMSA Finale at Daytona in 1979. We had never raced there before and we knew that long backstretch would be the most severe test our engine would ever encounter. I used colder sparkplugs and enfattenified (technical talk for richen) the fuel mixture beyond what we had found to be safe on the dyno. To be extra safe I put one of our EGT meters on the dash so we could be sure we weren't too lean. On the race track both Doc and I decided to look at the EGT at the end of that long back straight (after the throttle has been flat on the floor for about fifteen or twenty seconds) since we felt this is where we would see the highest temperature. In practice we both observed around 1250 degrees going into the banking and therefore thought we were safe. NOT! We didn't realize the temperature was dropping because we were detonating due to leanness caused by the failure of one of the electric fuel pumps (one pump wasn't enough to supply the big engine we were using). The weakest link broke (wrist-pin) and we windowed it. When I took it apart you could see the results of detonation in six holes. Had we been looking at the EGT gauge much earlier we might have been fore-warned of impending doom and I would have staved off my first engine failure for many more years. So here you can see one of the many pit-falls of monitoring EGT.

Now for the kicker. EGT is not a good way to determine fuel mixture for all the reasons I've mentioned. What I have tried to say is that there are many more variables than just air-fuel mixture that contribute to the EGT. For example, you can have two cylinders with different temperatures that have exactly the same air-fuel ratios. Also, the thermocouple, as simple as they are, can't be completely trusted. You can put in multiple thermocouples, have them terminate at approximately the same point, and they will record different temperatures. That is just one of many observations that erodes my trust in them. A much better way to observe mixture differences is with exhaust gas analysis of each individual exhaust pipe. Measuring the residual O2 or CO is the best way (outside of sending a little guy in there) to determine air-fuel mixture.

So, when some guy calls me up and says he's got a 57 Studebaker, 214 cubic inch with chrome reverse wheels, 600 Holley, full flow roller bearing camshaft, Mr. Gasket high lift rocker arms and he wants to know what his EGT should be. How can I be expected to answer this without first knowing how many watts he stereo boom box has, and I would have to know if that was RMS or peak-to-peak power.

There are many details in the gas exchange process which defy accurate explanation.

In conclusion, I will say that if you are trying to adjust fuel mixture or timing based solely on EGT - beware! Unless you have a baseline from which to start, such as dyno data, and fuel, it would be as fool-hearty to depend on the accuracy of EGT based fuel calibrations as it would be to recommend an optimum EGT to anyone.

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