Intelligent Gas Analyzer

Training

Five Gas Analysis Article

by Bernie Thompson

The smell of battle still hung in the hot dry air, but somehow the odor seemed different this time. We had landed many months ago in North Africa and had fought many battles in the African desert, but Rommel's armored division always won. That is until now. This sweet new smell was the scent of victory. After our many defeats at the hands of Rommel, how had this happened? My mind drifted back to the night before. It seemed like an eternity had passed, but it had been only a few hours. The battle had been at hand and I was filled with uncertainty, I could not sleep and walked around the camp thinking of what was to come at daybreak. The camp was quiet as I noticed an elderly officer across the camp reading by a faint light. Wondering who else was awake at this the early morning hour, I walked over. It was our new Commander in Chief, General Patton. He was reading Rommel's book on warfare. "Wow", I thought to myself, "He's reading the enemy's book!" Patton hearing me approach, paused for a moment and looked up. Noting my surprise, he explained, "In order to win against your opponent… you must first study him. You must understand him. Then and only then, can you predict his actions on the battle field. This knowledge (of your enemy) gives birth to victory." One must first know the enemy to overcome him or it… in this case, a problem automobile engine. Everyday in your service bay, you must fight an all out war… you against the vehicle! And in order to smell the sweet aroma of victory, you too must know your enemy. Now, let us take a close look into the enemy's eyes, for when you understand the enemy, that knowledge will tell you many things about the battle at hand... A chemical reaction powers the spark ignition, internal combustion engine. In order for this chemical reaction to take place, many things must occur in the correct order. When any of these events fail, this reaction will change. A knowledge of these changes will guide you in repairing the vehicle… "And lead you to Victory!"

The spark ignition (SI) engine draws air into the cylinder by creating a pressure differential. It does this by the downward movement of the piston with the intake valve in the open position. The air enters the engine at 14.7psi (at sea level). The atmospheric air is composed of approximately 79% nitrogen (N_2) and 21% oxygen (O_2). The fuel control system will then add a hydrocarbon (HC), in this case gasoline, into the intake or directly into the cylinder (Figure 1). The intake valve will then close and the piston will start its upward movement. As the piston movement increases the volume in the cylinder is forced to become smaller… Think of this as though thousands of people were standing in your shop parking lot. Imagine all of these people being forced into your service bay. As these people crowd the smaller area of your bay, soon the space in the room becomes limiting and they start to hit and bump into one another and the walls as the room fills. This bumping releases energy in the form of heat... This is similar to what is occurring in the cylinder…

The mechanical force of the piston moving upward puts energy into the gas and air molecules causing them to accelerate inside the cylinder. As these molecules accelerate, they collide with each other but no energy is lost. These collisions are perfectly elastic so when they collide, the energy is transferred from one molecule to another thus accelerating the molecule with which it collided. This creates heat energy that is transferred to the gases that are within the cylinder. Some of this heat energy is transferred to the cylinder walls. If the walls are the same temperature as the gas, then some gas atoms lose energy and some gain energy, thus the average temperature stays the same. If the walls are hotter than the gas, more atoms gain energy than lose energy and the temperature of the gas increases. If the compression occurs faster than the energy can dissipate into the cylinder walls, the temperature of the gas mixture will rise. This heat energy will be gained by the hydrocarbon chains which, under the right conditions, will cause complete combustion to occur. You can see that this heat energy is very important and it is crucial when igniting the air/fuel mixture. This heat energy reacts with the hydrocarbon chain to excite the bonds between the carbon and hydrogen and causes them to become unstable. The hotter the HC bond the more unstable it becomes and the easier it is to break this bond. Think of this as if several people were bound with steel bars. The steel restraint would be very rigid and would bond you to the other people. If a welding torch were used to put heat energy into the steel bars, soon, the people would be able to move by bending the bars. At the point the bar takes on enough energy, the bond can easily be broken. The purpose of the SI engine is to break the hydrogen – carbon bonds and the carbon – carbon bonds. The hydrogen is using energy to hold onto the carbon and the carbons are using energy to hold onto other carbons. If these bonds are broken then this energy is no longer needed to hold together the HC chain. This energy being freed from the HC bond is what powers the internal combustion engine. It is important to understand that the atoms are being held together with force. In order to break this bond more force will need to be applied to the bond than the force that is holding the atoms together. An example would be two large men locked together in combat. In order to separate these men more force would have to be applied than the fighters are using to hold together with. One person could not break these men apart.

It would take many men to separate these fighters. However, one man could knock the fighters over making them unstable. If the fighters were knocked over the second they hit the ground their grip would loosen. At this point it would be easier to separate them. In the SI engine when the compression is at its peak pressure the HC chains are at the same point the fighters were at when they hit the ground. The HC bond loosens for a spit second. At this precise point the spark needs to ionize across the spark plug electrodes. When the spark occurs, it applies more force than the HC bonds were held together with. The hydrogen and carbon will now be separated from one another.

However, if the hydrocarbon chain is completely broken down to its individual atoms and there is no oxygen to reform with, the hydrogen and carbon will reform into the same HC molecule it had been before it was broken apart. In this case no energy would be released. This is similar to you and your friends going to a dance. Your group enters the dance, but if there were no girls present, your group would break up. Several might go and get a drink, others would go to the restroom, but later you would all reform into the same group that you started with and would leave the dance together. On the other hand, if there are girls at the dance, your group would break apart. Due to the attraction of the girls you would form new bonds with the girls and then leave the dance with a new group or compound. This is similar to the combustion process. The oxygen and hydrocarbons are heated and become unstable. The bonds are then broken by the shock wave of the spark ionizing across the spark plug electrodes. The carbon being freed from the hydrogen is attracted by the oxygen.

The carbon then bonds with the oxygen making new compounds (figure 2). The atmosphere is comprised of 21% O_2 and 79% N_2. The nitrogen, N_2, is not a reactant. Its shear mass has to be accounted for because it produces heat energy during compression. During the reaction within the combustion chamber, the nitrogen will not release energy but as the reaction between the oxygen and hydrocarbons occur they will push against the nitrogen in the cylinder. The reactants that will release the energy upon ignition are hydrocarbons and oxygen. In a chemical reaction it is important to have the proper weight ratio of the compounds that are reacting with one another. If the weight ratio of the reactants is correct then at the end of the reaction neither chemical that you started with will be present.

This is a balanced reaction. In the internal combustion engine total combustion efficiency is not possible. Hydrocarbon chains will be forced into crevasses such as ring lands and valve pockets. The metal surfaces such as the cylinder wall will also take on heat allowing the HC chains to escape combustion. In this case the hydrocarbons and oxygen will break apart and recombine as CO and CO_2. The hydrogen will combine with oxygen making H20. Low levels of HC will also be present. In these conditions NO_x will be produced as well. In chemistry this is referred to as stochiometric. If you use the example of the dance and you have 50 boys (1lb of fuel) and 50 girls (14.7lbs of air) the boys and girls will break apart from the original groups and reform into new groups. Every boy will find a girl and the original groups will no longer exist. This would be stochiometric. However, if there were more girls or more boys this ratio would be off and the end product would still contain some of the original groups. As you can see with this example; if the weight ratios are out of balance the reaction cannot be complete.

When gasoline burns, the proper weight ratio is 14.7-lbs of air or the air pressure at sea level, with 1-lb of fuel. This is considered to be the proper chemical ratio or stochiometric. This is also referred to as a Lambda of 1. If by weight the air is greater than the fuel the Lambda will increase. Example, a lean mixture by 10% would equal 1.10 Lambda. If by weight the air is less than the fuel the Lambda will decrease. A rich mixture of 10% would equal .90 Lambda. An example of a rich mixture would be a burning candle (fuel) with a drinking glass over it. The candle (fuel) would use up all of the oxygen in the glass and stop burning leaving a large amount of fuel left in the glass, unburned. An example of a lean mixture would be a single match (fuel) burning with a drinking glass over it. The match (fuel) would burn completely but there would still be oxygen left in the glass. An example of a stochiometric mixture would be several matches burning with a drinking glass over it. In this case all of the matches (fuel) would burn completely and would use all of the oxygen in the glass. As the air/fuel mixture changes the burn rates also change. A rich mixture burns much faster than a lean mixture. This will change the gas traces at the tail pipe. Another example of a rich condition would be a forest fire. In a forest fire the trees and brush are very close together. The abundance of fuel makes a very hot flame front that can move from tree to tree very quickly. The heat from the moving flame front can cause the trees to burst into flames. The burning trees use up all of the oxygen before the tree has time to completely burn. This leaves partially burned trees standing in the forest. Inside the cylinder a rich air/fuel mixture burns in the same way. The abundance of fuel makes a very hot flame front that rapidly burns the hydrocarbons. The burning hydrocarbons use up all of the oxygen before all of the hydrocarbons burn. This leaves partially burned hydrocarbons or CO in the combustion chamber. In a rich condition the tailpipe readings show high levels of CO, low levels of O_2, slightly higher levels of hydrocarbons, and lower levels of NO_x. The NO_x formations are made at temperatures that are greater than 2500°F or at very high pressures. In a slightly rich condition the flame front is at its highest peak temperature and the NO_x is at a lower level. The reason for this is that the flame front is moving very rapidly which does not allow enough time to break the nitrogen down so it can combine with oxygen. In a rich condition, the lack of oxygen also contributes to the low level of NO_x produced. An example of a lean condition would be a prairie fire. Since the grass is further apart and not very abundant the flame front moves across the sparse grasslands slowly missing many clumps of grass. Inside the cylinder a lean air/fuel mixture burns the same way. The flame front moves slowly missing many of the hydrocarbon chains completely. This lean condition leaves the cylinder with high levels of hydrocarbons, high levels of oxygen, low levels of Co and low levels of CO_2. Since the flame front is moving slowly there is more time for the nitrogen to break apart and with the abundance of oxygen it easily combines to form high levels of NO_x. The effects of engine variables such as load, speed, ignition timing, and injector timing will all have an effect on the tail pipe emissions. It is not possible to cover all of these variables in this article but if you understand the basis of the chemical reaction you will have the basic tools you will need in order to understand the emission problems in your service bay.

Now that we have looked into the enemy's eyes and have a better understanding of the enemy, let us see what the enemy can tell us in the heat of battle. Our first example is a no-start. The exhaust probe was placed in the tail pipe and the engine was cranked for 8 seconds. The gas traces are then put into two formats. The first, (Figure 3) is a graph of the gases. The second (Figure 4) is a statistics chart of the gas traces. During this no-start the HC climbed to 4662ppm. This may seem high but in reality this is quite low. During a no-start condition the HC concentration can reach levels of 30,000ppm. The carbon monoxide levels are also low at a reading of 0.3716%.

The carbon dioxide levels are also low at a reading of 4.26%. The oxygen levels have not dropped very far, moving from 20.95% to 14.87%. The NOx levels have climbed to 176.9ppm while the Lambda dropped to 2.54 and the air/fuel ratio has dropped to 37.19 to 1.

Now the battle is in play. What can the enemy tell us? The key here is that oxygen was converted with hydrocarbons to form CO and CO2. This means a spark had to be present in the cylinder. In order to break the bonds between the hydrogen and carbon, a force must be applied that is greater than the force that is holding them together. This force is generated by the ignition coil. If the spark fails to ionize across the spark plug electrodes the hydrocarbon chain will not break down.

This second key is that the Lambda is 2.54. This is 2.5 times too lean. This engine has a low fuel delivery problem. The fuel pressure and volume or the injector on time or injector flow rate will need to be checked.

Our second example is also a no-start. The exhaust probe was placed in the tail pipe and the engine cranked over. The gas traces are then put into two formats. The first is a graph (Figure 5). The second is a statistics chart (Figure 6). The hydrocarbons climbed to 27030ppm. The carbon monoxide only reached .003663%. The carbon dioxide max is only 0.001811%. The oxygen dropped from 21.22% to 20.44%. The NOx rose to 840.75ppm. Lambda dropped to 0.877 with an air/fuel ratio of 12.81 to 1. What can we learn from these numbers? The hydrocarbon level of 27030ppm is good during a no-start. This is confirmed by the Lambda reading of .8771.

This is approximately 12% rich which would be correct for a cold start. The key to this puzzle is the CO and CO2. The oxygen did not combine with carbon. The cause of this is the lack of enough force to break down the hydrocarbon chain.

If the spark does not ionize across the spark plug electrodes the hydrocarbon chain will not break apart. Under this condition the carbon molecule will not be released so there will be no formation of CO or CO2. If the engine was running and then died there will be trace amounts of CO and CO2 left in the tail pipe. The engine will need to be cranked over for ten seconds to clear the exhaust system. Let the starter cool and then crank the engine over for eight to ten seconds to run the test. In this example the ignition system will need to be checked.

For our third example, we will look at another no-start condition. The exhaust probe was placed in the tail pipe and the engine was cranked (Figure 7). The hydrocarbons reached 16490ppm. The carbon monoxide levels climbed to 0.07075%. The carbon dioxide levels climbed to 2.14%. The oxygen had very little change occur. The NOx reached 119.7ppm.

The Lambda dropped to 1.27 with an air/fuel ratio of 18.67 to 1. At first this appears to be a lean air/fuel mixture. With a Lambda of 1.27 this is 27% too lean. The key to unraveling the puzzle is the HC and CO. With a reading of 2.14% CO2 you know that a spark occurred. The HC delivery at 16490ppm under good ignition would produce a higher CO reading than 0.07075%. In order for good ignition to occur there are many things that must happen in the correct order. If the spark does not occur at the correct time complete ignition cannot happen. This engine has a timing error. The ignition timing, firing order or cam timing will need to be checked.

For our forth example, we will look at a hard hot start. The exhaust probe was placed into the tail pipe and the engine was cranked over until the engine started (Figure 8). The hydrocarbons climbed to 25280ppm. The carbon monoxide rose to 7.49% with the carbon dioxide rising to 14.98%. The oxygen dropped from 21.15% to 1.39%. The NOx rose to 47.44ppm. The Lambda dropped to 0.60 with an air/fuel ratio of 8.835 to 1.

Now, what do these numbers mean? The battle is at hand, what is the enemy telling us? The HC is high at 25280ppm. The CO is also high at 7.49%. The Lambda is the key to unraveling this mystery. At 0.60 the air/fuel ratio is 40% too rich. Notice the bump in the CO2 and O2 trace. The CO2 started to climb, then dropped back down, then started to climb again. This shows that the over fueling problem only existed right at start up. The question here is where did the extra fuel come from? To find where the addition fuel came from, once the engine starts allow it to run until the gas traces stabilize which is about 10 to 15 sec. Now shut the engine off and wait about 2 min, then restart the engine. If the mixture is still very rich the problem is in the fuel injection system, the engine coolant temperature sensor is a good example. If the mixture is now good additional fuel is leaking into the intake manifold. The injectors, fuel regulator or fuel line will need to be checked in order to find this leak.

For our last example, we will examine a misfire on a 6 cylinder engine. In figure 9 the engine was running with the exhaust probe in the tail pipe. The cylinders were then killed one at a time by removing the spark from the cylinder. The hydrocarbons and oxygen are the traces to check. Since these are the chemicals reacting with each other, if the spark does not occur in the cylinder these gas traces will be the best reflection of the bad cylinder. Note the second cylinder killed did not change during the kill. On the second kill the HC rose only 60ppm. This 60ppm is HC residue left over from the first cylinder killed. What this means is that the HC had no change occur during the cylinder kill. The oxygen was 6% before the kill sequence and during number 2 the oxygen is still at 6%. The HC and oxygen not changing during the kill indicates this cylinder has no fuel being injected.

The fuel injector and/or the injection circuit will need to be checked on this engine. Understanding the gas traces and the chemical reaction that occurs in the combustion chamber is critical to targeting problems very quickly. These are only a few examples of how an exhaust gas analyzer can be used in your service bay. Now that you have looked into the eyes of the enemy and understand what his actions on the battle field will be, you too can obtain a victory in your service bay.