White Paper

Title: Oxidation and Reduction Efficiency Calculations
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Combustion (Carbon Oxidation) Efficiency:

One of the ways to look at the efficiency of an oxidation process is to evaluate how much of the fuel is oxidized by looking at the relative concentrations of the constituents of the output gas. For example, a gasoline engine oxidizes a blend of hydrocarbons (containing almost purely hydrogen and carbon atoms), to produce water vapor (H2O) and Carbon Dioxide (CO2). This oxidation process converts the Hydrogen and Carbon in the fuel to the combustion products above.. While water vapor and free Hydrogen are relatively difficult to measure, the carbon-bearing gases are easier to measure in both the input and output gas stream, and are generally either HC (Equivalent Selected Gas), CO (Carbon Monoxide) or CO2 (Carbon Dioxide). HC is the input hydrocarbon (fuel vapor), and is measured as hexane, propane or methane depending on the fuel selected - equivalent to 6, 3, or 1 carbon atoms per molecule. CO is an intermediate (half-way oxidized) gas, containing one carbon atom per molecule, and CO2 (fully oxidized carbon) contains one carbon atom per molecule.

As carbon atoms are neither gained or lost by the oxidation process but only converted from HC to CO or CO2, and the desired end product is CO2, it is relatively easy to determine just how efficient the process is in reaching the desired result. This is done by determining the conversion ratio of carbon from the input form (HC) to the desired output form (CO2). CO, being an intermediate oxidation form, is weighted at ‘0.5’ – to indicate that the carbon in it is 50% oxidized.

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Therefore, the numerator of the equation should contain all of the successfully oxidized carbon atoms (all of the CO2, and ½ of the CO) – and the denominator should contain all of the carbon atoms going into the oxidation process. Thus, the final equation is:

$$CE = \frac{[CO_2] + ([CO] \times 0.5)}{[CO_2] + [CO] + (n \times [HC])}$$

Where :

$[\mathrm{XX}] =$ Gas concentration in percent V/V.

$0.5 =$ Oxidation weight of CO. (1/2 fully oxidized Carbon)

$n =$ Number of carbon atoms in a molecule of the selected HC.

$n = 6$ for Hexane (Gasoline), 3 for Propane (LPG), 1 for Methane (CNG).

This method of looking at combustion efficiency as carbon oxidation efficiency has the combined advantages of being both mathematically and intuitively straightforward. It yields very useful combustion efficiency results, as it tells the user just how effective the process is at oxidizing the carbon in the fuel – a good indicator of overall performance.

CAT Converter Efficiency:

CE has an additional important benefit in that it may also be used to determine CAT oxidation efficiency if the pre CAT gas values can be determined or inferred. The way this is done is as follows:

First, the carbon oxidation inefficiency for the pre and post CAT gases is determined. To do this, the CE value for each gas set (calculated by the equation above) is subtracted from 1.000 to yield COI – Carbon Oxidation Inefficiency. Then, the ratio of these inefficiencies is determined and the result subtracted from 1.000. The 'reduction in oxidation inefficiency' caused by the CAT is the CAT oxidation efficiency.

Let's look at some values.

PRECAT CE = 93.62% *POSTCAT CE = 99.28%*

First determine for each gas set. CIE = 1-CE, so

PRECAT CIE = 6.38% POSTCAT CIE = 0.72%

CATCIE = POSTCAT CIE / PRECAT CIE CATCIE = 0.72 / 6.38 = 11.29%

CATCE = 1-CATCIE *CATCE = 88.71%*

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Basically, the CAT Carbon Oxidation Efficiency is:

$$\mathrm{CATCE} = 1 - (1 - \mathrm{POSTCE})/(1 - \mathrm{PRECE})$$

Where:

$$\mathrm{POSTCE} = \text{Post-CAT Carbon Oxidation Efficiency.}$$

$$\mathrm{PRECE} = \text{Pre-CAT Carbon Oxidation Efficiency.}$$

In the case above, CATCE = 1-(1-0.9928)/(1-0.9362) = 0.8871 = 88.71%

Some benchmarks are that the pre-CAT CE (engine CE) should be 95.0% or above, for a properly running engine, and the post-CAT CE should be 99.0% or above – which means the CAT converter efficiency should be 80.0% or greater.

When λ gets below about 0.980 or so, though, the CAT can no longer oxidize carbon very efficiently, so you have to be a little careful of this. With λ above 1.05 or so, lean misfire can occur, and the Pre-CAT CE gets pretty bad – and the CAT has to work very hard to clean up the exhaust gases.

Reduction (NOx to N_2 and O_2) Efficiency - CAT NRE:

$$\text{CAT NRE} = 1 - (\text{POSTCAT NOx} / \text{PRECAT NOx})$$

$$\textit{Where}:$$

$$\text{POSTCAT NOx} = \text{Post - CAT NOx Concentration in ppm.}$$

$$\text{PRECAT NOx} = \text{Pre - CAT NOx Concentration in ppm.}$$

The ability of the CAT to reduce NOx to N2 and O2 can also be assessed, and the CAT NRE (NOx Reduction Efficiency) is a relatively easy calculation to make:

Lets look at the numbers here, too:

PRECAT NOx = 437 ppm POSTCAT NOx = 76 ppm

CAT NRE = 1-(76/437) = 1-(0.174) = 82.6%

Closed Loop, but cold CAT gas readings:

And, lastly, it is important to realize that 'effective' pre CAT gas readings may be obtained without having to drill holes, etc – as they are equivalent to 'cold CAT' gas readings at the tailpipe. If the engine is allowed to warm up to the in idle mode, it can take several minutes for the tailpipe moisture to evaporate – which holds the CAT at 200F or so – and makes it quite inefficient. So, for several minutes after the engine is warm, the tailpipe readings closely approximate pre-CAT values if the engine is in closed loop fuel control mode.

At this time, idle-mode or ASM-mode exhaust gas readings may be taken. They will not pass emissions tests, but they will show the operating condition of the engine before the CAT cleans It up – quite valuable information.

Once the condensate is boiled off of the CAT, it begins to work pretty well, and you should see the HC, CO, and NOx values go down drastically. At this time, the post CAT gas readings can be taken, and the numbers crunched as above. You can also cool the CAT off with a garden hose to get it to quit processing the engine-out gasses (be a little careful here – slowly cool the CAT to avoid thermal shock) – and see what difference it makes to the gas readings and the CE calculation cold vs hot.

The best way to get pre-CAT gas values, of course, is to make a port in the exhaust system before the CAT, and get a gas sample there. While many techs are doing so by drilling a hole and putting a probe tip in there, it is better to use a 'HardSeal Port' – which is basically a crimp-in nutsert that you can thread a fitting into and then hook up a braided stainless

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steel Teflon sample line to for gas extraction. (Bridge Analyzers, Inc has the parts to do this.)

While this is the best way – it is intrusive, and it is good to have a practical alternative – like cooling the CAT method above.

Regardless, the combined use of Lambda and CE (and NRE) are quite valuable tools to assess and correct quite a variety of combustion and emissions problems.