White Paper

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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 oxygen and combustibles in 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). While water vapor and free Hydrogen are relatively difficult to measure, the carbon-bearing gases (HC, CO and CO2) are typically measured in a 4 or 5 gas analyzer. 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. (Gasoline, LPG or CNG) CO is an intermediate (half-way oxidized) gas, containing one carbon and oxygen atom per molecule, and CO2 (fully oxidized carbon) contains one carbon and 2 oxygen atoms 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:

$[XX]$ = Gas concentration in percent V/V.

(You have to convert PPM HC to % HC by dividing it by 10,000)

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

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

n = 12 for Hexane (Gasoline), 3 for Propane (LPG), 1 for Methane (CNG).

This method of looking at 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.

Engine Efficiency:

An internal combustion engine is not 100% efficient. It is difficult for an internal combustion engine to produce higher than 95% combustion efficiency even if it is well tuned and running correctly. 95% combustion efficiency is about the best that can be expected in engine-out gases.

Tuning for Performance:

While the performance goal is to make the engine as efficient as possible, the 95% CE target efficiency expressed above may not be desired, as running the engine off tune on the rich side of stoichometric (Lambda less than 1.000) assures higher oxygen utilization, and this is the limiting factor for power generation. To the degree that lambda is less than 1.000, combustion efficiency suffers. It is theoretically impossible for an engine with a Lambda of 0.950 to produce higher than 90% combustion (oxidation) efficiency due to the fact that there is simply not enough oxygen to fully oxidize the fuel. However, tuning on the rich side is common practice for high performance engines – so some balance has to be struck here. As Lambda effects CE, both parameters have to be evaluated together.

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When CE is maximum for a given Lambda, however, the engine is operating at peak-power-producing efficiency.

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, determine the work yet to be done. This is the the carbon oxidation inefficiency for the pre and post CAT gases. To do this, the CE value for each gas sample (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 CIE for each gas sample. CIE = 1-CE, so

PRECAT CIE = 6.38% **POSTCAT CIE = 0.72%**

You can clearly see here that there is far less 'work to be done' in the postcat gases than in the precat gases.

Calculate the Cat Inefficiency (how much is left to be done):

CATCIE = POSTCAT CIE / PRECAT CIE CATCIE = 0.72 / 6.38 = 11.29%
Subtract it from 1 to get the cat oxidation efficiency (how much the precat gases were cleaned up.

CATCE = 1-CATCIE ***CATCE = 88.71%***

The postcat gases are 88.71% more completely oxidized than the precat gases.

Basically, the CAT Carbon Oxidation Efficiency is:

$$CATCE = 1 - (1 - POSTCE)/(1 - PRECE)$$

$$\textit{Where:}$$

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

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

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 out 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.

Typically the CAT makes about a 10:1 improvement in oxidation, which would convert the 95.00% CE in engine out gases to 99.50% CE at the tailpipe.

Be careful of rich mixtures and lean misfire:

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. You may see pretty poor improvement in CE – just because the CAT is running out of oxygen.

With λ above 1.050 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, which can easily take it over its thermal limit.

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