Air fuel ratio – x-engineer.org

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Air fuel ratio definition

Thermal engines use fuel and oxygen (from air) to produce energy through combustion. To guarantee the combustion process, certain quantities of fuel and air need to be supplied in the combustion chamber. A **complete combustion** takes place when all the fuel is burned, in the exhaust gas there will be no quantities of unburnt fuel.

Air fuel ratio is defined as the ratio of air and fuel of a mixture prepared for combustion. For example, if we have a mixture of methane and air which has the air fuel ratio of 17.5, it means that in the mixture we have 17.5 kg of air and 1 kg of methane.

The ideal (theoretical) air fuel ratio, for a **complete combustion**, is called **stoichiometric air fuel ratio**. For a gasoline (petrol) engine, the stoichiometric air fuel ratio is around 14.7:1. This means that, in order to burn completely 1 kg of fuel, we need 14.7 kg of air. The combustion is possible even is the AFR is different than stoichiometric. For the combustion process to take place in a gasoline engine, the minimum AFR is around 6:1 and the maximum can go up to 20:1.

When the air fuel ratio is higher than the stoichiometric ratio, the air fuel mixture is called **lean**. When the air fuel ratio is lower than the stoichiometric ratio, the air fuel mixture is called **rich**. For example, for a gasoline engine, an AFR of 16.5:1 is lean and 13.7:1 is rich.

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Air fuel ratio formula

In the context of internal combustion engines, **air fuel ratio** (AF or AFR) is defined as the ratio between the mass of air m_a and mass fuel m_f, used by the engine when running:

AFR=mamf(1)

The inverse ratio is called fuel-air ratio (FA or FAR) and it's calculated as:

FAR=mfma=1AFR(1)

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Air fuel ratio for different fuels

In the table below we can see the stoichiometric air fuel ratio for several fossil fuels.

Fuel	**Chemical formula**	**AFR**
Methanol	CH_3OH	6.47:1
Ethanol	C_2H_5OH	9:1
Butanol	C_4H_9OH	11.2:1
Diesel	$C_{12}H_{23}$	14.5:1
Gasoline	C_8H_{18}	14.7:1
Propane	C_3H_8	15.67:1
Methane	CH_4	17.19:1
Hydrogen	H_2	34.3:1

Source: wikipedia.org

For example, in order to burn completely 1 kg of ethanol, we need 9 kg of air and to burn 1 kg of diesel fuel, we need 14.5 kg of air.

Spark ignition (SI) engines usually run on gasoline (petrol) fuel. The AFR of the SI engines varies within the range 12:1 (rich) to 20:1 (lean), depending on the operating condition of the engine (temperature, speed, load, etc.). Modern internal combustion engines operate as much as possible around the stoichiometric AFR (mainly for gas after-treatment reasons). In the table below you can see an example of a SI engine AFR, function of engine speed and torque.

Engine speed [rpm]

Engine torque [Nm]	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500
10	14	14.7	16.4	17.5	19.8	19.8	18.8	18.1	18.1	18.1	18.1	18.1	18.1
20	14	14.7	14.7	16.4	16.4	16.4	16.5	16.8	16.8	16.8	16.8	16.8	16.8
30	14	14.7	14.7	14.7	14.7	14.7	14.7	15.7	15.7	15.3	14.9	14.9	14.9
40	14.2	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	13.9	13.3	13.3	13.3
50	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.5	12.9	12.9	12.9
60	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.3	13.3	12.6	12.1	11.8
70	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	13.6	12.9	12.2	11.8	11.3
80	14.1	14.2	14.7	14.7	14.7	14.7	14.7	14.7	13.3	12.5	11.9	11.4	10.9
90	13.4	13.4	13.8	14.3	14.3	14.7	14.7	13.6	13.1	12.2	11.5	11.1	10.7
100	13.4	13.4	13.4	13.4	13.4	13.6	13.6	12.1	12.1	11.6	11.2	10.8	10.5
110	13.4	13.4	13.4	13.4	13.1	13.1	13.1	11.8	11.8	11.2	10.7	10.5	10.3
120	13.4	13.4	13.4	13.4	12.9	12.9	12.5	11.6	11.3	10.5	10.4	10.3	10.2
130	13.4	13.4	13.4	13.4	12.9	12.9	12.5	11.6	11.3	10.5	10.4	10.3	10.2
140	13.4	13.4	13.4	13.4	12.9	12.9	12.5	11.6	11.3	10.5	10.4	10.3	10.2

Image: Example of air fuel ratio (AFR) function of engine speed and torque

Compression ignition (CI) engines usually run on diesel fuel. Due to the nature of the combustion process, CI engines always run on lean mixtures, with AFR between 18:1 and 70:1. The main difference, compared with SI engines, is that CI engines run on **stratified** (non homogeneous) air fuel mixtures, while SI run on **homogeneous** mixtures (in case of port-injection engines).

The table above is entered in a Scilab script and a contour plot is generated.

```
EngSpd_rpm_X = [500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000 6500];
EngTq_Nm_Y = [10;20;30;40;50;60;70;80;90;100;110;120;130;140];
EngAFR_rat_Z = [14 14.7 16.4 17.5 19.8 19.8 18.8 18.1 18.1 18.1 18.1 18.1 18.1;
          14 14.7 14.7 16.4 16.4 16.4 16.5 16.8 16.8 16.8 16.8 16.8 16.8;
          14 14.7 14.7 14.7 14.7 14.7 14.7 15.7 15.7 15.3 14.9 14.9 14.9;
          14.2 14.7 14.7 14.7 14.7 14.7 14.7 14.7 14.7 13.9 13.3 13.3 13.3;
          14.7 14.7 14.7 14.7 14.7 14.7 14.7 14.7 14.7 14.5 12.9 12.9 12.9;
          14.7 14.7 14.7 14.7 14.7 14.7 14.7 14.7 14.3 13.3 12.6 12.1 11.8;
          14.7 14.7 14.7 14.7 14.7 14.7 14.7 14.7 13.6 12.9 12.2 11.8 11.3;
          14.1 14.2 14.7 14.7 14.7 14.7 14.7 14.7 13.3 12.5 11.9 11.4 10.9;
          13.4 13.4 13.8 14.3 14.3 14.7 14.7 13.6 13.1 12.2 11.5 11.1 10.7;
          13.4 13.4 13.4 13.4 13.4 13.6 13.6 12.1 12.1 11.6 11.2 10.8 10.5;
          13.4 13.4 13.4 13.4 13.1 13.1 13.1 11.8 11.8 11.2 10.7 10.5 10.3;
          13.4 13.4 13.4 13.4 12.9 12.9 12.5 11.6 11.3 10.5 10.4 10.3 10.2;
          13.4 13.4 13.4 13.4 12.9 12.9 12.5 11.6 11.3 10.5 10.4 10.3 10.2;
          13.4 13.4 13.4 13.4 12.9 12.9 12.5 11.6 11.3 10.5 10.4 10.3 10.2];
contour(EngSpd_rpm_X,EngTq_Nm_Y,EngAFR_rat_Z',30)
xgrid()
xlabel('Engine speed [rpm]')
ylabel('Engine torque [Nm]')
title('x-engineer.org')
```

Running the Scilab instructions above will generate the following contour plot:

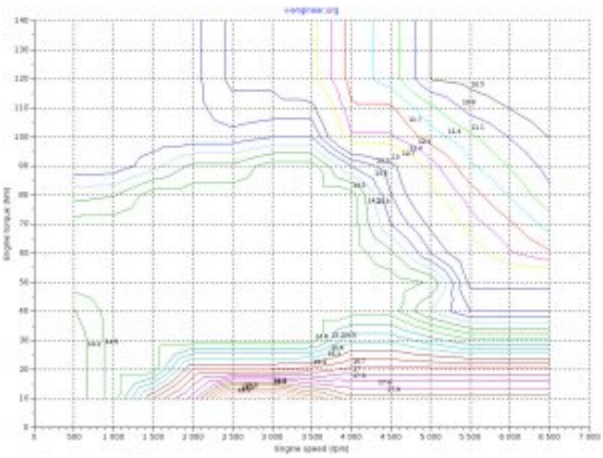

Image: Air fuel contour plot with Scilab

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How stoichiometric air fuel ratio is calculated

In order to understand how the stoichiometric air fuel ratio is calculated, we need to look at the **combustion process** of the fuel. Combustion is basically a chemical reaction (called **oxidation**) in which a fuel is mixed with oxygen and produces carbon dioxide (CO_2), water (H_2O) and energy (heat). Take into account that, in order for the oxidation reaction to occur we need an activation energy (spark or high temperature). Also, the net reaction is highly exothermic (with heat release).

$$\text{Fuel}+\text{Oxygen}\xrightarrow[\text{spark (SI)}]{\text{high temperature (CI)}}\text{Carbon dioxide}+\text{Water}+\text{Energy}$$

Example 1. For a better understanding, let’s look at the **oxidation reaction of methane**. This is a pretty common chemical reaction, since methane is the primary component of natural gas (in proportion of around 94 %).

Step 1. Write the chemical reaction (oxidation)

$$CH_4+O_2 \rightarrow CO_2+H_2O$$

Step 2. Balance the equation

$$CH_4+2\cdot O_2 \rightarrow CO_2+2\cdot H_2O$$

Step 3. Write down the standard atomic weight for each atom

$$\begin{aligned}\text{Hydrogen} &= 1.008 \text{ amu}\\ \text{Carbon} &= 12.011 \text{ amu}\\ \text{Oxygen} &= 15.999 \text{ amu}\end{aligned}$$

Step 4. Calculate the mass of fuel, which is 1 mol of methane, made up from 1 atom of carbon and 4 atoms of hydrogen.

$mf=12.011+4\cdot 1.008=16.043$ g

Step 5. Calculate the mass of oxygen, which consists of 2 moles, each mol made up from 2 atoms of oxygen.

$mo=2\cdot 15.999\cdot 2=63.996$ g

Step 6. Calculate the necessary mass of air which contains the calculated mass of oxygen, taking into account that air contains around 21 % oxygen.

$ma=10021\cdot mo=10021\cdot 63.996=304.743$ g

Step 7. Calculate the air fuel ratio using equation (1)

$AFR=mamf=304.74316.043=18.995$

The calculated AFR for methane is not exactly as specified in the literature. The difference might come from the fact that, in our example, we made several assumptions (air contains only 21 % oxygen, the products of the combustion are only carbon dioxide and water).

Example 2. The same method can be applied for the combustion of gasoline. Considering that gasoline is made up from **iso-octane** (C_8H_{18}), calculate the **stoichiometric air fuel ratio for gasoline**.

Step 1. Write the chemical reaction (oxidation)

$C8H18+O2\rightarrow CO2+H2O$

Step 2. Balance the equation

$C8H18+12.5\cdot O2\rightarrow 8\cdot CO2+9\cdot H2O$

Step 3. Write down the standard atomic weight for each atom

HydrogenCarbonOxygen=1.008 amu=12.011 amu=15.999 amu

Step 4. Calculate the mass of fuel, which is 1 mol of iso-octane, made up from 8 atoms of carbon and 18 atoms of hydrogen.

$mf=8\cdot 12.011+18\cdot 1.008=114.232$ g

Step 5. Calculate the mass of oxygen, which consists of 12.5 moles, each mol made up from 2 atoms of oxygen.

$mo=12.5\cdot 15.999\cdot 2=399.975$ g

Step 6. Calculate the necessary mass of air which contains the calculated mass of oxygen, taking into account that air contains around 21 % oxygen.

$$m_a = \frac{100}{21} \cdot m_o = \frac{100}{21} \cdot 399.975 = 1904.643 \text{ g}$$

Step 7. Calculate the air fuel ratio using equation (1)

$$AFR = \frac{m_a}{m_f} = \frac{1904.643}{114.232} = 16.673$$

Again, the calculated stoichiometric air fuel ratio for gasoline is slightly different that the one provided in literature. Thus, the result is acceptable since we made a lot of assumptions (gasoline contains only iso-octane, air contains only oxygen in proportion of 21 %, the only products of combustion are carbon dioxide and water, the combustion is ideal).

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Lambda air fuel ratio

We have seen what is and how to calculate the stoichiometric (ideal) air fuel ratio. In reality, internal combustion engines do not work exactly with ideal AFR, but with values close to it. Therefore we'll have an ideal and a actual air fuel AFR ratio. The ratio between the actual air fuel ratio (AFR_{actual}) and the ideal/stoichiometric air fuel ratio (AFR_{ideal}) is called **equivalence air fuel ratio** or **lambda** (λ).

$$\lambda = \frac{AFR_{actual}}{AFR_{ideal}} \quad (3)$$

For example, the ideal air fuel ratio for a gasoline (petrol) engine is 14.7:1. If the actual/real AFR is 13.5, the equivalence factor lambda will be:

$$\lambda = \frac{13.5}{14.7} = 0.92$$

Depending on the value of lambda, the engine is told to work with lean, stoichiometric or rich air fuel mixture.

Equivalence factor	**Air fuel mixture type**	**Description**
$\lambda < 1.00$	Rich	There is not enough air to burn completely the amount of fuel; after combustion there is unburnt fuel in the exhaust gases
$\lambda = 1.00$	Stoichiometric (ideal)	The mass of air is exact for a complete combustion of the fuel; after combustion there is no excess oxygen in the exhaust and no unburnt fuel
$\lambda > 1.00$	Lean	There is more oxygen than required to burn completely the amount of fuel; after combustion there is excess oxygen in the exhaust gases

Depending on the type of fuel (gasoline or diesel) and the type of injection (direct or indirect), an internal combustion engine can function with lean, stoichiometric or rich air fuel mixtures.

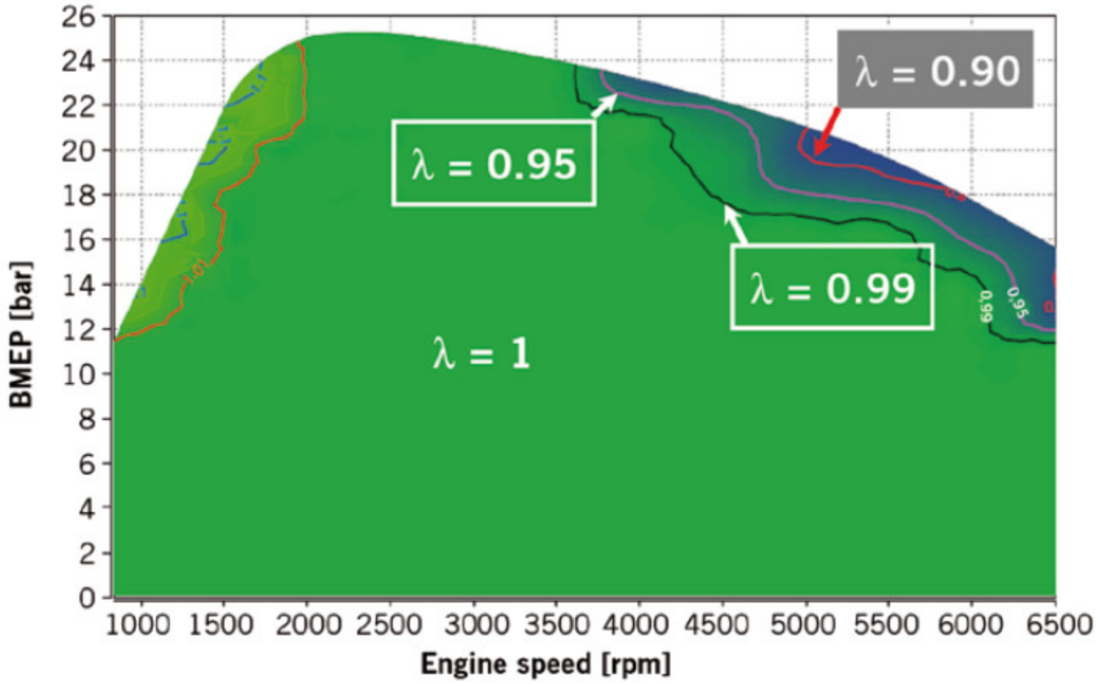

Image: Ecoboost 3-cylinder direct injection gasoline engine (lambda map)
Credit: Ford

For example, the Ford Ecoboost 3-cylinder engine runs with stoichiometric air fuel ratio for idle to medium engine speed and complete load range, and with rich air fuel mixture at high speed and load. The reason for which it runs with rich mixture at high engine speed and load is **engine cooling**. The additional fuel (which will remain unburnt) is injected to absorb heat (through evaporation), reducing this way the temperature in the combustion chamber.

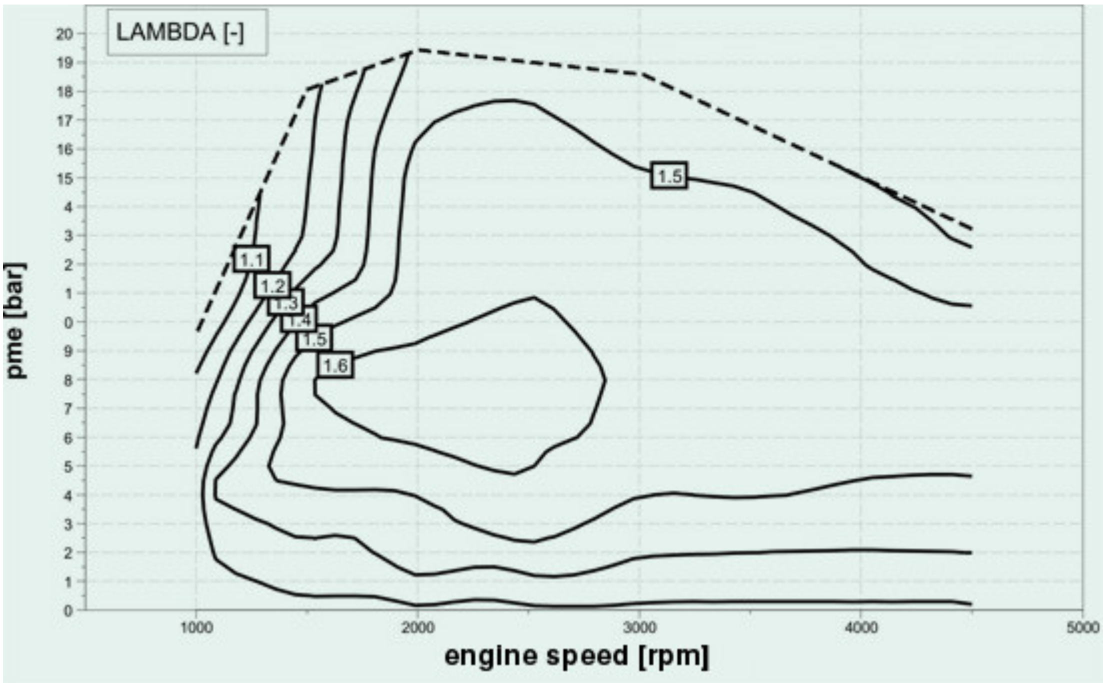

Image: Diesel engine (lambda map)
Credit: wtz.de

A compression ignition (diesel) engine runs all the time with **lean air fuel mixture**, the value of the equivalence factor (λ) depending on the engine's operating point (speed and torque). The reason for this is the working principle of a diesel engine: controlling load not through air mass (which is always in excess) but through fuel mass (injection time).

Remember that a **stoichiometric equivalence factor** ($\lambda = 1.00$) means an air fuel ratio of 14.7:1 for gasoline engines and 14.5:1 for diesel engines.

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Air fuel ratio and engine performance

The engine performance in terms of power and fuel consumption is highly dependent on the air fuel ratio. For a gasoline engine, the lowest fuel consumption is obtained at lean AFR. The main reason is that there is enough oxygen available to burn completely all the fuel which translates in mechanical work. On the other hand, the maximum power is obtained with rich air fuel mixtures. As explained before, putting more fuel in the cylinder at high engine load and speed, cools down the combustion chamber (through fuel evaporation and heat absorption) which allows the engine to produce maximum engine torque thus maximum power.

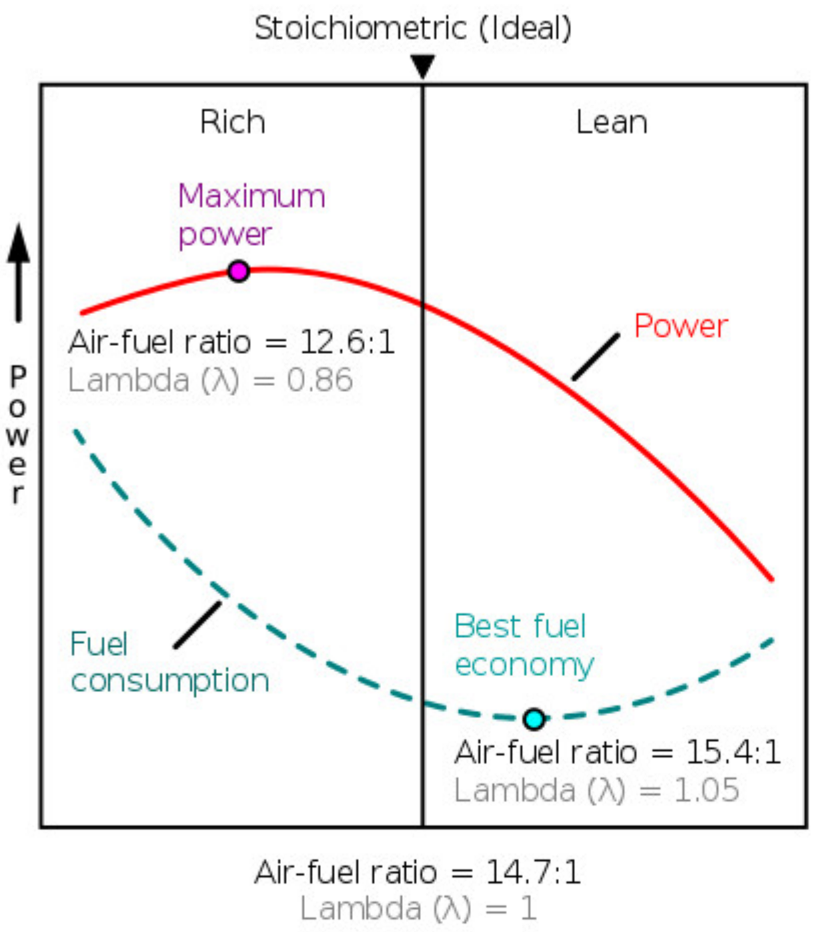

Image: Engine power and fuel consumption function of air fuel ratio (lambda)

In the figure above we can see that we can not get the maximum power of the engine and the lowest fuel consumption with the same air fuel ratio. The lowest fuel consumption (best fuel economy) is obtained with lean air fuel mixtures, with an AFR of 15.4:1 and an equivalence factor (λ) of 1.05. The maximum engine power is produced with rich air fuel mixtures, with an AFR of 12.6:1 and an equivalence factor (λ) of 0.86. With a stoichiometric air fuel mixture ($\lambda = 1$), there is a compromise between maximum engine power and minimum fuel consumption.

Compression ignition (diesel) engines always run on lean air fuel mixtures ($\lambda > 1.00$). Most of the modern diesel engines run with λ between 1.65 and 1.10. The maximum efficiency (lowest fuel consumption) is obtained around $\lambda = 1.65$. Increasing the fuel amount above this value (going towards 1.10) will produce more soot (unburnt fuel particles).

There is an interesting study performed by R. Douglas on 2-stroke cycle engines. In his doctoral thesis "*Closed Cycle Studies of a Two-Stroke Cycle Engine*", R. Douglas comes with a mathematical expression of the **combustion efficiency** (η_λ) function of equivalence factor (λ).

For spark ignition (gasoline engine) with an equivalence factor between 0.80 and 1.20, the combustion efficiency is:

$\eta\lambda=-1.6082+4.6509\cdot\lambda-2.0746\cdot\lambda2(4)$

For compression ignition (diesel engine) with an equivalence factor between 1.00 and 2.00, the combustion efficiency is:

$\eta\lambda=-4.18+8.87\cdot\lambda-5.14\cdot\lambda2+\lambda3(5)$

For diesel engines, if the equivalence factor goes above 2.00, the combustion efficiency is maximum (1.00 or 100 %).

We can use a Scilab script to plot the variation of the combustion efficiency function of the equivalence factor.

```
lmbd_g = [0.80:0.01:1.20];
lmbd_d = [1.00:0.01:2.00];
eff_lmbd_g = -1.6082+4.6509*lmbd_g-2.0746*lmbd_g.^2;
eff_lmbd_d = -4.18+8.87*lmbd_d-5.14*lmbd_d.^2+lmbd_d.^3;
plot(lmbd_g,eff_lmbd_g,'b','LineWidth',2)
hold
plot(lmbd_d,eff_lmbd_d,'r','LineWidth',2)
xgrid()
xlabel('$\lambda \text{ [-]}$')
ylabel('$\eta_{\lambda} \text{ [-]}$')
title('x-engineer.org')
legend('gasoline','diesel',4)
```

Running the Scilab instructions above outputs the following graphical window.

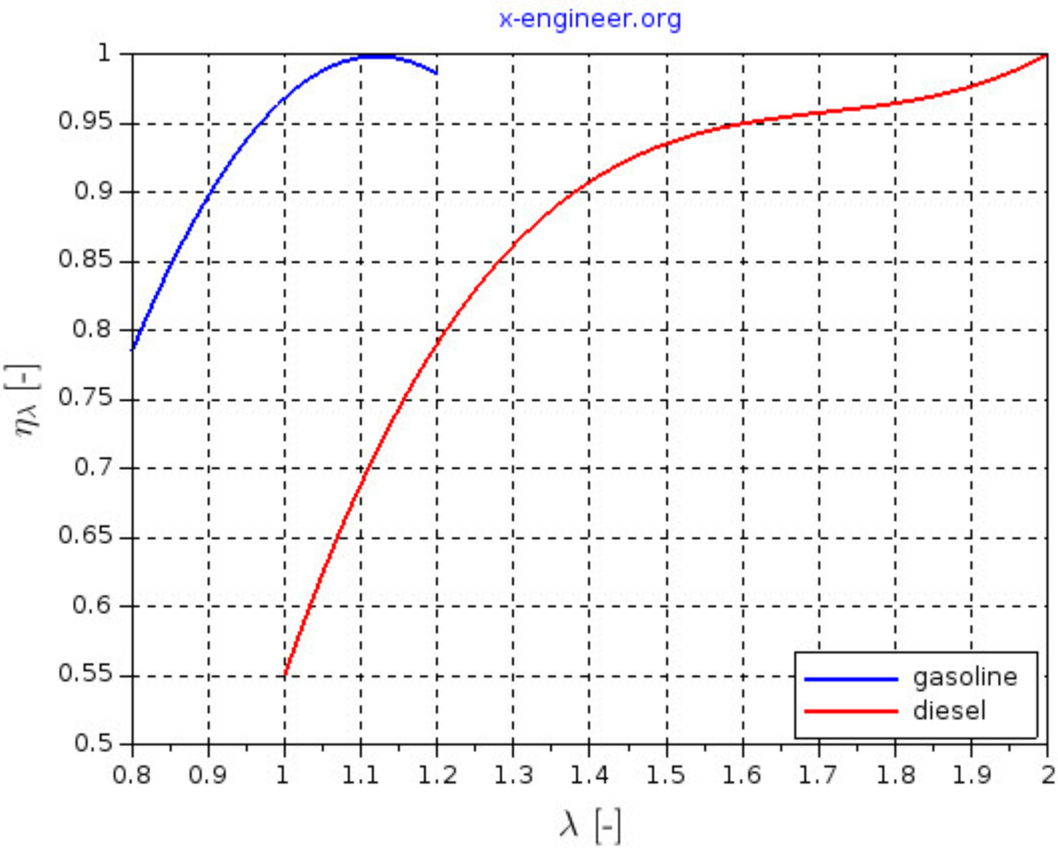

Image: Combustion efficiency function of equivalence factor

As you can see, the compression ignition (diesel) engine, at stoichiometric air fuel ratio has a very low combustion efficiency. The best combustion efficiency is obtained at λ = 2.00 for diesel and λ = 1.12 for spark ignition (gasoline) engines.

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Air fuel ratio calculator

m_a [g]	Fuel type	λ [-]
m_f [g]		η_λ [%]

Observation: The combustion efficiency is only calculated for diesel and gasoline (petrol) fuel, using equations (4) and (5). For the other fuels, the combustion efficiency calculation is not available (NA).

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Impact of air fuel ratio on engine emissions

Internal combustion engine exhaust gas emissions depend heavily on the air fuel ratio (equivalence factor). The main exhaust gas emissions in ICE are summarised in the table below.

Exhaust gas emission	Description
CO	carbon monoxide
HC	hydrocarbon
NOx	nitrogen oxides
Soot	unburnt fuel particles

For a gasoline engine, CO, HC and NOx exhaust gas emissions are heavily influenced by **air fuel ratio**. CO and HC are mainly produced with rich air fuel mixture, while NOx with lean mixtures. So, there in no fixed air fuel mixture for which we can obtain the minimum for all exhaust emissions.

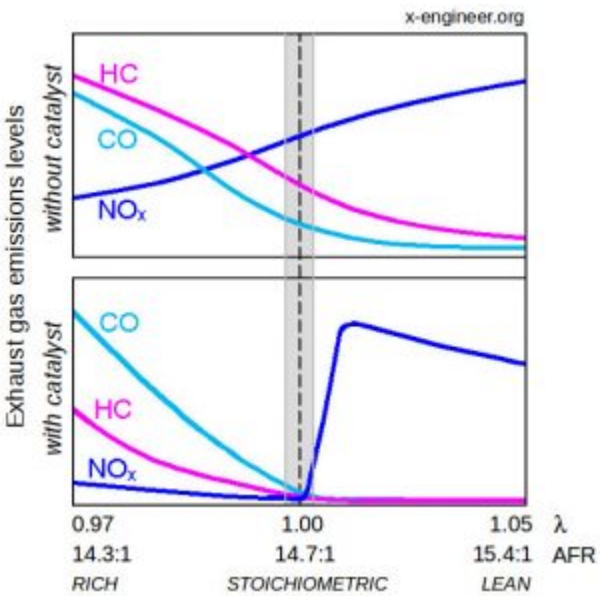

Image: Gasoline engine catalyst efficiency function of air fuel ratio

A three way catalyst (TWC), used for gasoline engines, has the highest efficiency when the engine operates in a narrow band around stoichiometric air fuel ratio. The TWC converts between 50 … 90 % of hydrocarbons and 90 … 99 % of carbon monoxide and nitrogen oxides, when the engine runs with $\lambda = 1.00$.

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Lambda closed-loop combustion control

In order to meet the exhaust gas emissions regulations, it is critical for internal combustion engines (especially gasoline) to have an accurate control of the air fuel ratio.

Therefore, all of the modern internal combustion engines have **closed-loop control for air fuel ratio (lambda)**.

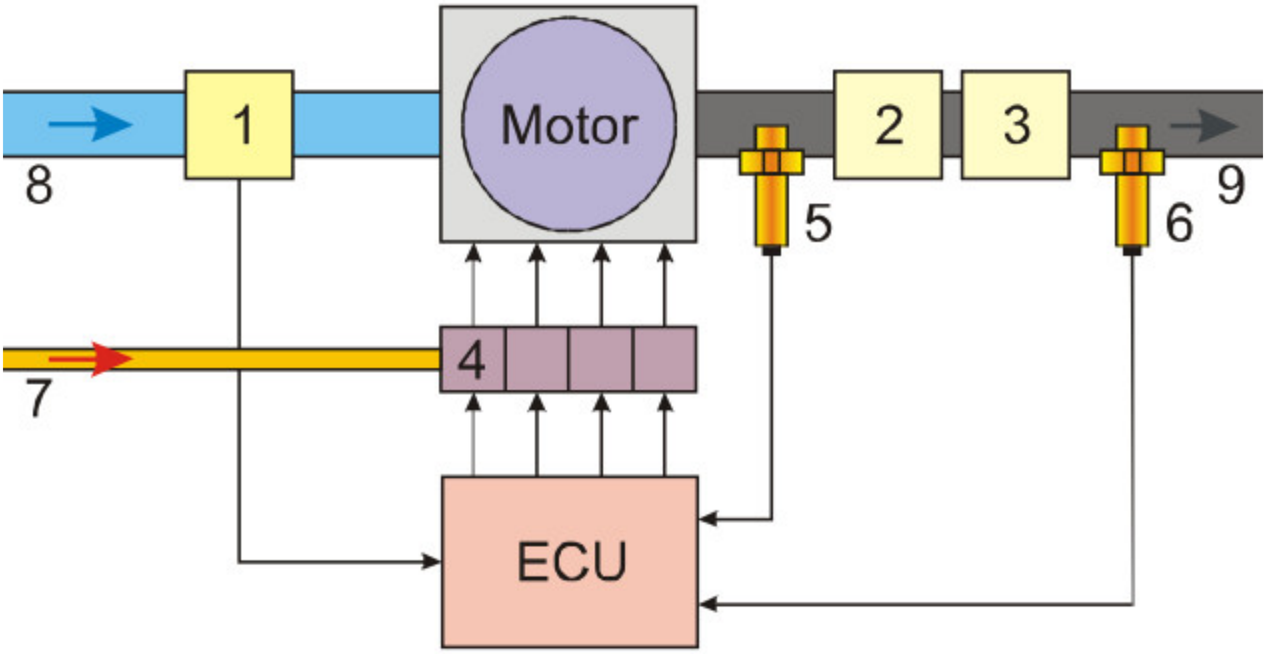

Image: Internal combustion engine closed-loop lambda control (gasoline engines)

1. air mass flow sensor
2. primary catalyst
3. secondary catalyst
4. fuel injector
5. upstream lambda (oxygen) sensor
6. downstream lambda (oxygen) sensor
7. fuel supply circuit
8. intake manifold
9. exhaust manifold

The critical component for the system to work is the **lambda (oxygen) sensor**. This sensor measures the level of oxygen molecules in the exhaust gas and sends the information to the engine electronic control unit (ECU). Based on the value of the oxygen sensor reading, the gasoline engine ECU will adjusts the level of fuel mass in order to keep the air fuel ratio around the stoichiometric level ($\lambda = 1.00$).

For example (gasoline engines), if the level of oxygen molecules is above the threshold for stoichiometric level (therefore we have a lean mixture), at the next injection cycle, the injected fuel amount will be increased in order to make use of the excess air. Bear in mind that the engine will always transition from **lean** mixture to **rich** mixture between injection cycles, which will give an “average” of stoichiometric air fuel mixtures/ratio.

For diesel engines, since it always runs on lean air fuel ratio, lambda control is performed in a different manner. The end goal being still the same, control of the exhaust gas emissions.

For any questions or observations regarding this tutorial please use the comment form below.

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