2. **Composition of Combustion Gas**

2.1 **Fossil Fuels**

Fuels are characterized by their physical state (gaseous, liquid, solid) and by their chemical composition (see Table 2-1).

**Gaseous Fuels**

The extracted crude gas is processed directly on the earth gas field. It consists mainly of methane. In the case of „sweet“ natural gases, which are free of sulfur compounds, mainly only steam is separated. In the case of „sour“ natural gases, which contain up to 20% hydrogen sulfide and organic sulfur compounds, these components are almost completely eliminated. The residual total sulfur then amounts to only 100 - 200 mg/m$^3$ [1.3] Some crude natural gases also require the separation off higher hydrocarbons, carbon dioxide and nitrogen. The most common method for that is gas washing. In the case of crude gases with a high nitrogen content (up to 50%) the methane is liquefied at temperatures of -161 °C for the separation. Natural gas from various deposits is usually mixed in order to ensure a quality which remains as constant as possible. Table 1-2 specifies guide values for the composition of natural gas. A differentiation is made between natural gas L and natural gas H, the latter exhibiting a higher methane content.

Coke oven gas is obtained as a byproduct in coke production. Here bituminous coal is heated indirectly to 1300 °C under exclusion of air. The gases released in the process are quenched by water injection. In this way the tarry portions of the crude gas are precipitated. Afterward the gas is liberated from further undesired components such as benzene, ammonia and hydrogen sulfide. The principal components of the coke oven gas are hydrogen and methane in accordance with Table 1-2.

Top gases accumulate in blast furnaces in metallurgy. In view of their low content of combustible components, primarily CO, they are designated as weak gases.

Liquefied gas consists mainly of propane (C$_3$H$_8$). Butane (C$_4$H$_{10}$) is partly admixed in small quantities.

Biomass is formed during the oxygen-free decomposition of biomass. It consists mainly of methane and carbon dioxide. Small amounts up to 1 % sulfur hydrogens, ammonia, etc. have to be separated.

**Liquid Fuels**

The basis of liquid fuels is crude oil. The crude product extracted from the earth is separated from gases and salt water. This treated product is designated as crude oil (petroleum) and transported further. The cleaned and treated base product and intermediate product of processing (distillation) are designated as mineral oil or mineral oil products. The composition is very complicated and diverse due to the extremely complex formation of crude oil. Until now over 500 components have been discovered in crude oil.

For practical concerns, the viscosity and the density are the most important criteria of differentiation.
The density varies between 700 and 1000 kg/m$^3$. Accordingly a differentiation is made between light (EL) and heavy (S) fuel oil. Fuel oils exhibit a carbon contents between 84 and 87% and hydrocarbon contents between 11 and 14%. According to the deposit, the sulfur content can amount to up to 6%. Light fuel oil has sulfur contents around 1%; heavy oil between 2 and 5%. Heavy oil additionally contains ash in the range of 0.0001 to 0.05%. Fuel oils possess small quantities of nitrogen, which is still organically bound, which can lead to NO$_X$ emissions. Diesel fuel essentially differentiates itself from light fuel oil only through a reduced content of sulfur and nitrogen.

**Solid Fuels**

The analysis of the solid fuels is always specified in mass percent of the anhydrous and ash free (waf) substance. In addition the mass content of the liquid water (w), the ash (a) and the volatile components (Ft) is listed.

Bituminous coal consist of a complicated mixture of organic hydrocarbon compounds. It is graded in accordance with the percentage of the volatiles (see Table 1-2). Gassing coals exhibit the highest percentage with up to 45%, anthracite coal the lowest with 10%. The lower the percentage of volatiles is, the higher the carbon content is. The sulfur contents are around 1%, the nitrogen around 1.5% and the acidic contents in the range of 2 to 8%. The distinguishing feature of all coal is the ash content, which in part can even amount to more than 10%.

In the case of coke the volatiles are nearly completely expelled as was already described in coke oven gas. This then consists mostly of carbon.

Owing to its very heterogeneous chemical and physical properties lignite is more difficult to characterize than other solid fuels. The distinguishing feature of crude lignite is the very high content of water and of volatile components. On the basis of the external quality, a differentiation is essentially made between soft, hard and glance lignite. As a rule lignite must be dried for industrial combustion. It is then used pulverized as lignite dust and formed as lignite briquette. Coke is also produced from lignite by thermal treatment.

Finally wood is specified with an average composition as a solid fuel as well in Table 1-2. The distinguishing feature is the high oxygen content. As a result wood is relatively easy to ignite.

**2.2 Oxygen and Air Demand**

Oxygen is required in accordance with the overall reaction equations

\[
C + O_2 \rightarrow CO_2
\]
\[
H_2 + \frac{1}{2} O_2 \rightarrow H_2O
\]
\[
CH_4 + 2 O_2 \rightarrow CO_2 + 2 H_2O
\]
\[
CO + \frac{1}{2} O_2 \rightarrow CO_2
\]
\[
C_2H_6 + \frac{7}{2} O_2 \rightarrow 2 CO_2 + 3 H_2O
\]
\[
C_nH_m + \left( n + \frac{m}{4} \right) O_2 \rightarrow n \cdot CO_2 + \frac{m}{2} H_2O
\]
\[
S + O_2 \rightarrow SO_2 .
\]
In view of the oxidation of sulfur, the O₂ demand is disregarded in the following, since only some fuels contain sulfur and in these cases, as a rule, the sulfur can be disregarded for the O₂ demand in view of the comparatively low concentration. For the sake of expedience, a differentiation is made between gaseous fuels and liquid as well as solid fuels, since the composition for gases is specified in volume percent and for other fuels in mass percent.

**Gaseous Fuels**

In the case of gaseous fuels the specific O₂ demand \( \left[ \frac{m_{O_2}^i}{m_i^s} \right] \) amounts to

\[
\tilde{O} = \sum \tilde{x}_i \cdot \nu_i - \tilde{x}_{O_2,f} .
\]  

(2-1)

Here
- \( \tilde{x}_i \left[ \frac{m_i^s}{m_i^s} \right] \) is the content by volume of the component i in fuel
- \( \nu_i \left[ \text{Mol O}_2 / \text{Mol}_i = \frac{m_{O_2}}{m_i} \right] \) is the stoichiometric number of i for complete oxidation
- \( \tilde{x}_{O_2,f} \) is the content by volume of O₂ possibly contained in the fuel

The following applies to the density of the gaseous fuels

\[
\rho_f = \sum \tilde{x}_i \cdot \rho_i
\]

(2-2)

\( \rho_i \) being the density of the individual components. These calculations are carried out for a typical natural gas and top gas respectively as examples in Table 2-2.

**Liquid and Solid Fuels**

In the case of liquid and solid fuels the specific O₂ demand in \( \text{kg}_{O_2} / \text{kg}_f \) amounts to

\[
O = \sum x_{if} \cdot \frac{\tilde{M}_{O_2}}{\tilde{M}_i} - x_{O_2,f}
\]

(2-3)

Here
- \( x_{if} \left[ \text{kg} / \text{kg}_f \right] \) is the content by mass of the component i in the fuel,
- \( \nu_i \left[ \text{kmol O}_2 / \text{kmol}_i \right] \) is the stoichiometric number as before,
- \( \tilde{M} \left[ \text{kg} / \text{kmol}_i \right] \) is the molar mass available from O₂ and i,
- \( x_{O_2,f} \) is the content by mass of the O₂ in the fuel.

These calculations are carried out for some fuels in Table 2-3 as examples.

The specific air demand depends on the O₂ concentration in the air. The following applies to the molar air demand \( \left[ \frac{m_{L}^s}{m_i^s} \right] \)

\[
\tilde{L} = \frac{\tilde{O}}{\tilde{x}_{O_2,L}}
\]

(2-4)
and the following to the mass related air demand $[\text{kg}_L / \text{kg}_f]$

$$L = \frac{O}{x_{O,L}}. \quad (2-5)$$

Here $x_{O,L}$ and $x_{O,L}$ are the volume concentration and mass concentration respectively of $O_2$ in the air for combustion. The following connection exists between the molar and mass related air demand

$$L = \tilde{L} \cdot \frac{\rho_L}{\rho_f} \quad (2-6)$$

$\rho_L$ and $\rho_f$ being the densities of the air and the fuel respectively.

Table 2-4 displays the composition of the air. The volume concentration of the $O_2$ in the air amounts to 0.21 and the mass concentration to 0.23. As a result the air demand specified in Table 2-5 ensues for some typical fuels. Assuming an ash content of 9% and a humidity of 1% for the anthracite coal, the air demand then decreases in relation to the actual coal mass by 10% to 10.9 kg/kg$_f$.

The ratio of the quantity of air actually fed in to the quantity of air stoichiometrically required is denoted as excess air number $\lambda$.

$$\lambda = \frac{\text{Actual air input}}{\text{Stoich. air demand}}.$$  

2.3 Composition of Combustion Gas

In accordance with the overall reaction equation cited before, the combustion gas contains CO$_2$ and H$_2$O, from the air and O$_2$ and N$_2$, as well as for reasons of equilibrium the unburned components CO and H$_2$ and the dissociated components O, OH, H and so forth. The first four components (CO$_2$, H$_2$O, O$_2$, N$_2$) can be calculated from the molecular balances of the four elements C, H, O and N. For each further component an equilibrium relation must be given. In the following the composition of the combustion gas is universally specified and then it is shown at which conditions the unburned and dissociated components can be disregarded.

2.3.1 Molar Balances

The molar balances for C, H$_2$, O$_2$ and N$_2$ are available to calculate the composition of the combustion gas. The moles of these four species fed in with the fuel and the air must be equal to the moles drawn off with the combustion gas. Again a differentiation is made between gaseous as well as solid and liquid fuels. For the gaseous one the moles are related to volume, for the other one the moles are related to mass.

Input of moles

With the components of gaseous fuels the following C-moles are fed in:
\[ \bar{\nu}_C = \bar{x}_{\text{CH}_2} + \bar{x}_{\text{COF}} + \sum n \cdot \bar{x}_{(\text{C}_i\text{H}_n)_r} + \bar{x}_{\text{CO}_2} \cdot \]  \hspace{2cm} (2-7)

\( \text{H}_2 \) moles are fed in both with the fuel and with the humidity of the air

\[ \bar{\nu}_{\text{H}} = 2 \cdot \bar{x}_{\text{CH}_2} + \bar{x}_{\text{H}_2} + \frac{m}{2} \cdot \bar{x}_{(\text{C}_i\text{H}_n)_r} + \bar{x}_{\text{H}_2\text{O}L} \cdot \lambda \cdot \bar{L} \cdot \]  \hspace{2cm} (2-8)

The input with the humidity is comparable very low. The following accordingly applies to the \( \text{O}_2 \) and \( \text{N}_2 \) moles fed in

\[ \bar{\nu}_{\text{O}_2} = \bar{x}_{\text{CO}_2} + \frac{1}{2} \bar{x}_{\text{COF}} + \left( \bar{x}_{\text{O}_3\text{L}} + \frac{1}{2} \cdot \bar{x}_{\text{H}_2\text{O}L} \right) \cdot \lambda \cdot \bar{L} \]  \hspace{2cm} (2-9)

\[ \bar{\nu}_{\text{N}_2} = \bar{x}_{\text{N}_2} + \bar{x}_{\text{N}_3\text{L}} \cdot \lambda \cdot \bar{L} \]  \hspace{2cm} (2-10)

respectively.

Here \( \bar{x}_i \) and \( \bar{x}_{il} \) are the volume concentration of \( i \) in the fuel or in the air respectively and \( \bar{\nu}_i \) is the fuel-related molar quantity of \( C, \text{H}_2, \text{O}_2 \) and \( \text{N}_2 \) in units of \( [\text{m}^3/\text{mol}] \).

The composition of liquid and solid fuels is specified in mass percent. Therefore, the mass fractions have to be transferred into volume fractions using the molar density. The following ensues for the molar quantities fed in with \( \nu_i \) in \( \text{m}^3/\text{kgf} \):

\[ \nu_C = \frac{x_C \cdot \frac{1}{M_C} \cdot \frac{1}{\bar{\rho}}}{\bar{\rho}} \]  \hspace{2cm} (2-11)

\[ \nu_{\text{H}_2} = \left( \frac{1}{2} \cdot x_h \cdot \frac{1}{M_H} + x_w \cdot \frac{1}{M_{\text{H}_2\text{O}}} + x_{\text{H}_2\text{O}L} \cdot \lambda \cdot \frac{\bar{L}}{M_{\text{H}_2\text{O}}} \right) \cdot \frac{1}{\bar{\rho}} \]  \hspace{2cm} (2-12)

\[ \nu_{\text{O}_2} = \left( \frac{1}{2} \cdot x_o \cdot \frac{1}{M_O} + x_{\text{O}_3\text{L}} \cdot \frac{\lambda \cdot \bar{L}}{M_{\text{O}_2}} + \frac{1}{2} \cdot x_{\text{H}_2\text{O}L} \cdot \frac{\lambda \cdot \bar{L}}{M_{\text{H}_2\text{O}}} \right) \cdot \frac{1}{\bar{\rho}} \]  \hspace{2cm} (2-13)

\[ \nu_{N_2} = \left( \frac{1}{2} \cdot x_n \cdot \frac{1}{M_N} + x_{N_3\text{L}} \cdot \frac{\lambda \cdot \bar{L}}{M_{N_2}} \right) \cdot \frac{1}{\bar{\rho}} \]  \hspace{2cm} (2-14)

Here \( x_c, x_h, x_o, x_n, x_w \) are the contents by mass of \( C, \text{H}, \text{O}, \text{N} \) and liquid water in the fuel, \( x_{iL} \) is the mass concentration of \( i \) in air and

\[ \bar{\rho} = \frac{p}{(R \cdot T)} \]  \hspace{2cm} (2-15)

is the molare density which value at standard condition is \( \bar{\rho}_0 = 0.0446 \text{ kmol} / \text{m}^3 \).
For the humidity the following results when the temperature is known and the relative humidity $\varphi$

$$\tilde{x}_{H_{2}O} = x_{H_{2}O} \cdot \frac{\tilde{M}_{L}}{M_{H_{2}O}} = \frac{p_{H_{2}O_{eq}}}{p/\varphi - p_{H_{2}O_{eq}}} = \frac{\varphi \cdot p_{H_{2}O_{eq}}}{p} \quad (2-16)$$

$p$ being the total pressure and $p_{H_{2}O_{eq}}$ the equilibrium pressure or the vaporation steam pressure. The following applies to this

$$p_{H_{2}O_{eq}} = p_{0} \cdot \exp \left[ -\frac{\Delta h}{R_{H_{2}O}} \left( \frac{1}{T} - \frac{1}{T_{0}} \right) \right] \quad (2-17)$$

with, for example, the reference conditions $p_{0} = 0.018$ bar and $T_{0} = 293^\circ$C ($\Delta h = 2500$ kJ/kg and $R_{H_{2}O} = 0.464$ kJ/(kg·K)). $p_{H_{2}O_{eq}} = 0.012$ bar and $\tilde{x}_{H_{2}O} = 0.008$ ensues, for example, for ambient air of 10 °C and 60% humidity.

Output of moles

The moles are removed with the components in the combustion gas. With the gas concentration $\tilde{x}_{i} \left[ m_{i}/m_{gas} \right]$ the following ensues:

- for gaseous fuels with the fuel-related quantity of gas $\tilde{\nu} \left[ m_{i}/m_{gas} \right]$

  $$\tilde{\nu}_{C} = \tilde{\nu} \cdot \left( \tilde{x}_{CO_{2}} + \tilde{x}_{CO} \right) \quad (2-18)$$

  $$\tilde{\nu}_{H_{2}} = \tilde{\nu} \cdot \left( \tilde{x}_{H_{2}O} + \tilde{x}_{H_{2}} + \frac{1}{2} \tilde{x}_{OH} \right) \quad (2-19)$$

  $$\tilde{\nu}_{O_{2}} = \tilde{\nu} \cdot \left( \tilde{x}_{O_{2}} + \tilde{x}_{CO_{2}} + \frac{1}{2} \cdot \tilde{x}_{CO} + \frac{1}{2} \cdot \tilde{x}_{H_{2}O} + \frac{1}{2} \cdot \tilde{x}_{O} + \frac{1}{2} \cdot \tilde{x}_{OH} \right) \quad (2-20)$$

  $$\tilde{\nu}_{N_{2}} = \tilde{\nu} \cdot \tilde{x}_{N_{2}} \quad (2-21)$$

- for liquid and solid fuels with the specific gas amount $\nu \left[ m_{i}/m_{gas} \right]$

  $$\nu_{C} = \nu \cdot \left( \tilde{x}_{CO_{2}} + \tilde{x}_{CO} \right) \quad (2-22)$$

  $$\nu_{H_{2}} = \nu \cdot \left( \tilde{x}_{H_{2}O} + \tilde{x}_{H_{2}} + \frac{1}{2} \cdot \tilde{x}_{OH} \right) \quad (2-23)$$

  $$\nu_{O_{2}} = \nu \cdot \left( \tilde{x}_{O_{2}} + \tilde{x}_{CO_{2}} + \frac{1}{2} \cdot \tilde{x}_{CO} + \frac{1}{2} \cdot \tilde{x}_{H_{2}O} + \frac{1}{2} \cdot \tilde{x}_{O} + \frac{1}{2} \cdot \tilde{x}_{OH} \right) \quad (2-24)$$

  $$\nu_{N_{2}} = \nu \cdot \tilde{x}_{N_{2}} \quad (2-25)$$
At temperatures below 2500°C, the molar quantities, by the trace elements O, H and so on, can be disregarded in the balances.

The specific quantity of combustion $\bar{v}$ or $\bar{v}$ gas results from the condition

$$\sum \bar{x}_i = 1.$$  \hfill (2-26)

If the combustion can be considered to be complete, all components except $\text{CO}_2$, $\text{H}_2\text{O}$, $\text{O}_2$ and $\text{N}_2$ can then be disregarded, thus the concentrations of these four components can already be calculated from the balances mentioned above. However an equilibrium equation is required for any further components.

### 2.3.2 Equilibrium

Every chemical reaction runs its course not completely, but rather only as far as equilibrium. This is specified by the law of mass action

$$K(T) = \frac{\prod \bar{x}^{\nu}_P}{\prod \bar{x}^{\nu}_E}. \quad (2-27)$$

Here $\bar{x}_i$ and $\nu_i$ signify the concentration and the stoichiometric number respectively of the product (P) and the input product (E). The correlation between temperature and the equilibrium number is given by the following equation

$$K(T) = K_0 \cdot \exp \left( -\frac{\Delta \tilde{h}}{R \cdot T} \right) \quad (2-28)$$

$\Delta \tilde{h}$ being the molar enthalpy of reaction and $R$ the universal gas constant. Table 2-6 shows these values for several reactions. Figure 2-1 shows the temperature dependence. The following equilibrium applies, for example, to the hydrogen combustion $\text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O}$

$$K_2(T) = \frac{\bar{x}_{\text{H}_2\text{O}}}{\bar{x}_{\text{H}_2} \cdot \bar{x}_{\text{O}_2}^{1/2}}. \quad (2-29)$$

The index of $K$ corresponds to the numbering in Figure 2-1. From this the following ensues for the hydrogen concentration

$$\bar{x}_{\text{H}_2} = \frac{\bar{x}_{\text{H}_2\text{O}}}{\bar{x}_{\text{O}_2}^{1/2}} \cdot \frac{1}{K_2(T)}. \quad (2-30)$$

$$K_3(T) = \frac{\bar{x}_{\text{CO}_2}}{\bar{x}_{\text{CO}} \cdot \bar{x}_{\text{O}_2}^{1/2}} \quad (2-31)$$
and
\[ \tilde{x}_{\text{CO}} = \tilde{x}_{\text{CO}_2} \cdot \frac{1}{\tilde{x}_{\text{O}_2}^{\frac{1}{2}}} K_{1}(T) \quad (2-32) \]

apply accordingly to the CO combustion \( \text{CO} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2 \).

From both these equilibriums the equilibrium of the so-called homogeneous water-gas reaction \( \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \) can be derived by replacing the \( \text{O}_2 \)-concentration

\[ K_{1}(T) = \frac{\tilde{x}_{\text{CO}_2} \cdot \tilde{x}_{\text{H}_2}}{\tilde{x}_{\text{H}_2\text{O}} \cdot \tilde{x}_{\text{CO}}} \quad (2-33) \]

In addition the equilibriums exist with the radicals such as, \( \text{O}_2 \leftrightarrow \text{O} + \text{O} \) for example,

\[ K_{5}(T) = \frac{\tilde{x}_{\text{O}_2}}{\tilde{x}_{\text{O}}^2} \quad (2-34) \]

\[ K_{4}(T) = \frac{\tilde{x}_{\text{H}_2\text{O}}}{\tilde{x}_{\text{H}} \cdot \tilde{x}_{\text{OH}}} \quad (2-35) \]

and \( \text{H}_2 \leftrightarrow \text{H} + \text{H} \)

\[ K_{6}(T) = \frac{\tilde{x}_{\text{H}_2}}{\tilde{x}_{\text{H}}^2} \quad (2-36) \]

The equilibrium of the three radicals \( \text{O}, \text{H} \) and \( \text{OH} \) can be calculated from these last three equilibriums when the \( \text{CO}_2, \text{H}_2\text{O} \) and \( \text{O}_2 \) concentrations are known. When determining the combustion gas composition as many equilibrium calculations must be taken into account as additional components to the four components \( \text{CO}_2, \text{H}_2\text{O}, \text{O}_2 \) and \( \text{N}_2 \) are to be considered.

The following text demonstrates the influence of the dissociation.

### 2.3.3 Combustion Gas Composition when \( \lambda = 1 \)

The composition of combustion gas for excess air numbers of one is shown in Figure 2-2 for natural gas at both temperatures of 1200 °C and 1800 °C. The concentrations were calculated using the equations in the two preceding sections. At temperatures of 1200 °C the CO and \( \text{H}_2 \) progressions exhibit a high gradient at \( \lambda = 1 \). In the case of excess air numbers approximately larger than 1.05 the CO and \( \text{H}_2 \) concentrations become negligibly small. If the excess air number drops slightly under one, the CO and \( \text{H}_2 \) concentrations increase sizably. Therefore, to be on the safe side, the excess air number must always be larger than one for a complete combustion.

At the temperature of 1800 °C the CO and \( \text{H}_2 \) concentrations change much less with the excess air number. Both concentrations are now so high that, as a rule, these may no longer be disregarded, as will be demonstrated later. At temperatures above 1800 °C two
equilibrium equations must therefore be considered, e.g. \( \text{CO}_2 \rightarrow \text{CO} + \frac{1}{2} \text{O}_2 \) and \( \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2 \).

Additionally it is discernible in Figure 2-2 that at \( \lambda < 1 \) the \( \text{O}_2 \) concentrations become very small. Therefore, as a rule, \( \text{O}_2 \) in the combustion gas can be disregarded in gasification processes.

### 2.3.4 Combustion Gas Composition at \( \lambda > 1 \)

Figure 2-3 shows the composition of combustion gas for natural gas with an excess air number of 1.2 as an example. This figure makes clear how the dissociated components CO and \( \text{H}_2 \) as well as the radicals \( \text{O}, \text{H}, \text{and OH} \) increase sharply with the temperature. These components can be disregarded at temperatures under 1800 °C, since they then no longer influence the temperature of the flame. It is sufficient to calculate these only from the specified equilibrium calculations. The \( \text{O} \) concentration however decisively determines the \( \text{NO}_x \) emission. Both effects will be dealt with later.

In the following a gas temperature lower than 1800 °C is assumed so that all components except \( \text{CO}_2, \text{H}_2\text{O}, \text{O}_2 \) and \( \text{N}_2 \) can be disregarded.

For gaseous fuels ensues for the concentrations from the Eq. (2-18) until (2-21) using also the Eq. (2-7) until (2-9) such as Eq. (2-1) und (2-4) for the air demand

\[
\tilde{x}_{\text{CO}_2} = \frac{\tilde{\upsilon}_c}{\tilde{\upsilon}}, \quad \tilde{x}_{\text{H}_2\text{O}} = \frac{\tilde{\upsilon}_{\text{H}_2}}{\tilde{\upsilon}}, \quad \tilde{x}_{\text{O}_2} = \frac{\tilde{\upsilon}_{\text{O}_2}^*}{\tilde{\upsilon}}, \quad \tilde{x}_{\text{N}_2} = \frac{\tilde{\upsilon}_{\text{N}_2}}{\tilde{\upsilon}}. \quad (2-37)
\]

Here \( \tilde{\upsilon}_c, \tilde{\upsilon}_{\text{H}_2}, \text{and } \tilde{\upsilon}_{\text{N}_2} \) are the input moles according to the Eq. (2-7), (2-8) and (2-10). For the oxygen yields

\[
\tilde{\upsilon}_{\text{O}_2}^* = (\lambda - 1) \cdot \tilde{L} \cdot \tilde{x}_{\text{O}_2L}, \quad (2-38)
\]

which is the input of the non-reacting oxygen. For the specific amount of the combustion gas follows from Eq. (2-26)

\[
\tilde{\upsilon} = \tilde{\upsilon}_c + \tilde{\upsilon}_{\text{H}_2} + \tilde{\upsilon}_{\text{O}_2}^* + \tilde{\upsilon}_{\text{N}_2}. \quad (2-39)
\]

For liquid and solid fuels ensues for the concentrations analogously from Eq. (2-23) until (2-24), (2-3) and (2-5)

\[
\tilde{x}_{\text{CO}_2} = \frac{\upsilon_c}{\upsilon}, \quad \tilde{x}_{\text{H}_2\text{O}} = \frac{\upsilon_{\text{H}_2}}{\upsilon}, \quad \tilde{x}_{\text{O}_2} = \frac{\upsilon_{\text{O}_2}}{\upsilon}, \quad \tilde{x}_{\text{N}_2} = \frac{\upsilon_{\text{N}_2}}{\upsilon}. \quad (2-40)
\]

Here \( \upsilon_c, \upsilon_{\text{H}_2}, \text{and } \upsilon_{\text{N}_2} \) are the input mole flow according to the Eq. (2-11), (2-12) and (2-14). For the oxygen follows
\[ \nu_{O_2}^* = (\lambda - 1) \cdot L \cdot x_{O_2, \lambda} \cdot \frac{1}{M_{O_2} \cdot \rho} \]  
(2-41)

which is again the input of the non-reacting oxygen. From Eq. (2-26) we get

\[ \nu = \nu_C + \nu_{H_2} + \nu_{O_2}^* + \nu_{N_2}, \]  
(2-42)

and with Eq. (2-14) neglecting the fuel N

\[ \nu = \nu_C + \nu_{H_2} + \frac{L}{\rho} \left( \lambda - x_{O_2, \lambda} \right). \]  
(2-43)

For the density of the combustion gas always

\[ \rho = \sum \bar{x}_i \cdot \rho_i \]  
(2-44)

is valid with \( i = CO_2, H_2O, O_2 \) and \( N_2 \).

The gas must be dried for analyses, since \( H_2O \) influences the adsorption of infrared radiation. Gas analyses then relate to the dry gas (index \( dr \)). The quantity of gas and the concentrations then amount to

\[ \tilde{\nu}_{dr} = \tilde{\nu} - \tilde{\nu}_{H_2}, \]  
(2-45)

or

\[ \nu_{dr} = \nu - \nu_{H_2} , \]  
(2-46)

\[ \tilde{x}_{CO_2, dr} = \frac{\tilde{\nu}_C}{\tilde{\nu}_{dr}}, \quad \tilde{x}_{O_2, dr} = \frac{\tilde{\nu}_{O_2}^*}{\tilde{\nu}_{dr}}, \quad \tilde{x}_{N_2, dr} = \frac{\tilde{\nu}_{N_2}}{\tilde{\nu}_{dr}} \]  
(2-47)

or

\[ \tilde{x}_{CO_2, dr} = \frac{\nu_C}{\nu_{dr}}, \quad \tilde{x}_{O_2, dr} = \frac{\nu_{O_2}^*}{\nu_{dr}}, \quad \tilde{x}_{N_2, dr} = \frac{\nu_{N_2}}{\nu_{dr}} \]  
(2-48)

respectively.

The Figures (2-4) and (2-5) depict the combustion gas concentrations for the both fuels natural gas and light oil. It is clear how \( CO_2 \) and \( H_2O \) decrease with the excess air number and \( O_2 \) increases. For natural gas the \( H_2O \) concentration is double the concentration of the \( CO_2 \). For oil both concentration are similar. The difference between the wet and the dry concentration is the highest for natural gas.

Figure 2-6 shows the composition of the combustion gas of further fuels. For coals the concentration of \( CO_2 \) is higher than that of \( H_2O \). Because the compositions of coals vary considerably with the source the figure gives a range for the values. For methanol the \( H_2O \)
concentration is double the value of CO$_2$ because the ratio of C/H is 1/4 similar as for methane. However, the concentrations are higher than those of methane. This is caused by the fact that methanol contains oxygen and therefore less air has to feed. For biogas a mean value is depicted for the range of composition given in Table 2-1. Here, the concentrations of CO$_2$ and H$_2$O are similar as for oil. However the values are higher than those for oils because biogas has a lower air demand. The combustion gas of top gases consists mainly of CO$_2$. For this fuel the CO$_2$ concentration has the highest values.

Figure 2-7 depicts the belonging specific amounts of flue gas. These are depending on fuel and increase according to Eq. (2-39) and (2-43) linearly with the excess air number. The density of the flue gas is shown in Figure 2-8. Light oil and natural gas give a lower density as air, anthracite and top gas give a higher density as air.

2.3.5 Hypostoiometric Combustion ($\lambda < 1$)

In accordance with Figure 2-2 the oxygen in the gas can be disregarded in hypostoiometric combustion. The gas then consists of the components CO$_2$, H$_2$O, CO, H$_2$ and N$_2$. The four molar balances and the equilibrium relation (2-32) CO$_2$ + H$_2$ $\leftrightarrow$ H$_2$O + CO are available to calculate these components. From this the following ensues for the CO$_2$ concentration

$$\tilde{x}_{CO_2} = \frac{A}{2} + \left( \frac{A^2}{4} - B \right)^{1/2} \quad (2-49)$$

with

$$A = \frac{\tilde{v}_{C} + \tilde{v}_{H_2} - 2 \cdot \tilde{v}_{O_2} (1 - K_1)}{\tilde{v} \cdot (1 - K_1)}$$

$$B = \frac{K_1 \cdot \tilde{v}_{C} \cdot (\tilde{v}_{C} - 2 \cdot \tilde{v}_{O_2})}{\tilde{v}^2 \cdot (1 - K_1)}$$

and for the other concentrations

$$\tilde{x}_{CO} = \frac{\tilde{v}_{C} - \tilde{v} \cdot \tilde{x}_{CO_2}}{\tilde{v}} \quad (2-50)$$

$$\tilde{x}_{H_2O} = \frac{2 \cdot \tilde{v}_{O_2} - \tilde{v} \cdot \tilde{x}_{CO_2} - \tilde{v}_{C}}{\tilde{v}} \quad (2-51)$$

$$\tilde{x}_{H_2} = \frac{\tilde{v} \cdot \tilde{x}_{CO_2} + \tilde{v}_{C} - 2 \cdot \tilde{v}_{O_2} + \tilde{v}_{H_2}}{\tilde{v}} \quad (2-52)$$

$$\tilde{x}_{N_2} = \frac{\tilde{v}_{N_2}}{\tilde{v}} \quad (2-53)$$

with the input mole flow $\tilde{v}_C$, $\tilde{v}_{H_2}$, $\tilde{v}_{O_2}$, $\nu_{H_2}$ according to Eq. (2-7) until (2-10). From Eq. (2-25) follows for the specific gas amount
\[ \bar{\nu} = \bar{\nu}_c + \bar{\nu}_{H_2} + \bar{\nu}_{N_2}. \]  

(2-54)

For liquid and solid fuels \( \bar{\nu}_i \) is to be replaced by \( \nu_i \).

Figure 2-9 shows as an example the composition of combustion gas for natural gas for two temperatures. Since the equilibrium number \( K_i \) in accordance with Figure 2-1 is only slightly temperature dependent, this also applies to the concentrations.

### 2.3.6 Determination of \( \lambda \)

If the quantity of air is unknown or if false air intake through doors and inequalities, \( \lambda \) must often be determined from the gas concentration. The following ensues from the molar balances when the CO\(_2\) and CO concentrations are known

\[ \lambda = 1 + \frac{\bar{\nu}_{st,dr}}{L} \left( \frac{\bar{x}_{CO,\text{st}}}{\bar{x}_{CO_2} + \bar{x}_{CO}} - 1 \right) \]  

(2-55)

or the following when the O\(_2\) concentration is known

\[ \lambda = 1 + \frac{\bar{\nu}_{st,dr}}{L} \frac{\bar{x}_{O_2}}{\bar{x}_{O_{2,l}} + \bar{x}_{O_2}}. \]  

(2-56)

Here \( \bar{\nu}_{st,dr} \) is the dry quantity of gas in stoichiometric combustion (\( \lambda = 1 \)). \( \bar{x}_{CO} = 0 \) in complete combustion (\( \lambda > 1 \)). The following can be set for approximate calculations

\[ \bar{\nu}_{st,dr} \approx \bar{L}. \]  

(2-57)

### 2.3.7 Dew-Point Temperature of Water

When cooling flue gas a condensation of the steam contained in. It occurs such that the saturation pressure or equilibrium pressure \( p_{eq}(\vartheta_{dew}) \), which decreases with the temperature, falls below the partial pressure of the steam \( p_{H_2O} \). The accompanying temperature is called dew-point temperature \( \vartheta_{dew} \). To determine this the partial and equilibrium pressure must be thus calculated.

The following applies to the ratio of the partial pressures of the water vapor and dry gas \( p_{G\text{dr}} \)

\[ \frac{p_{H_2O}}{p_{G\text{dr}}} = \frac{p_{H_2O}}{p - p_{H_2O}} = \frac{\bar{\nu}_{H_2O}}{\bar{\nu}_{dr}} \]  

(2-58)

\( p \) being the total pressure. From this the following ensues

\[ p_{H_2O} = p \cdot \frac{1}{1 + \frac{\bar{\nu}_{H_2O}}{\bar{\nu}_{dr}}} \approx p \cdot \frac{\bar{\nu}_{H_2O}}{\bar{\nu}_{dr}}. \]  

(2-59)
The following is obtained for the moist flue gas in mass percentage

\[ x_{\text{H}_2\text{O}} = \frac{p_{\text{H}_2\text{O}}}{p - p_{\text{H}_2\text{O}}} \cdot \frac{R_L}{R_{\text{H}_2\text{O}}} \quad (2-60) \]

in which the gas constant of the dry air can be introduced as the gas constant of the flue gas. Figure 2-10 shows the humidity of the flue gas for the three typical fuels as an example and to be precise with and without taking into account the humidity introduced with the combustion air. For more precise calculations the air humidity should thus be taken into account particularly when the excess air numbers are high.

The equilibrium pressure amounts to

\[ p_{\text{eq}} = p_0 \cdot \exp \left[ \frac{-\Delta h_{\text{vap}}}{R_{\text{H}_2\text{O}}} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right] \quad (2-16) \]

\( R_{\text{H}_2\text{O}} = 0.462 \ \text{kJ/(kg} \cdot \text{K}) \) being the gas constant and \( \Delta h_{\text{vap}} = 2360 \ \text{kJ/kg} \) the evaporation enthalpy when the reference conditions are \( T_0 = 333 \ \text{K} \left(\approx 60^\circ \text{C} \right) \) and \( p_0 = 0.20 \ \text{bar} \). From the condition \( p_{\text{eq}} = p_{\text{H}_2\text{O}} \) the following then results for the dew-point temperature

\[ T_{\text{dew}} = \left[ \frac{1}{T_0} + \frac{R_{\text{H}_2\text{O}}}{\Delta h_{\text{vap}}} \cdot \ln \frac{p_0}{p_{\text{H}_2\text{O}}} \right]^{-1} \quad (2-61) \]

This is represented in Figure 2-11. According to that the dew point is all the higher, the lower the excess air number is. Natural gas possesses the highest dew point temperatures.
### Combustible gases

<table>
<thead>
<tr>
<th></th>
<th>CH$_4$</th>
<th>C$_2$H$_6$</th>
<th>$\Sigma$C$_n$H$_m$</th>
<th>H$_2$</th>
<th>CO</th>
<th>CO$_2$</th>
<th>N$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas L</td>
<td>82</td>
<td>3</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Natural gas H</td>
<td>93</td>
<td>3</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Coke-oven gas</td>
<td>25</td>
<td>-</td>
<td>3</td>
<td>55</td>
<td>5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Blast-furnace gas</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1 - 2</td>
<td>24-28</td>
<td>10 - 23</td>
<td>50 - 60</td>
</tr>
<tr>
<td>Liquified gas (propane)</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Biogas</td>
<td>50 - 60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>40 - 50</td>
<td>-</td>
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### Liquid fuels

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>H</th>
<th>S</th>
<th>O + N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel oil (light)</td>
<td>86</td>
<td>13</td>
<td>&lt;0.1</td>
<td>0.005 – 0.05</td>
</tr>
<tr>
<td>Fuel oil (heavy)</td>
<td>85</td>
<td>11</td>
<td>1 – 5</td>
<td>1</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>86</td>
<td>14</td>
<td>&lt;0.005</td>
<td>-</td>
</tr>
<tr>
<td>Petrol</td>
<td>85</td>
<td>15</td>
<td>&lt;0.002</td>
<td>-</td>
</tr>
<tr>
<td>Methanol (CH$_3$OH)</td>
<td>37.5</td>
<td>12.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ethanol (C$_2$H$_5$OH)</td>
<td>52</td>
<td>13</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Solid fuels

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>H</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>Fl.</th>
<th>w</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Gas flame coal</td>
<td>81 - 85</td>
<td>6 - 7</td>
<td>1</td>
<td>8 - 10</td>
<td>1.5</td>
<td>30 - 40</td>
<td>1 - 4</td>
<td>3 - 10</td>
</tr>
<tr>
<td>- Fat coal</td>
<td>88 - 90</td>
<td>5</td>
<td>1</td>
<td>3 - 5</td>
<td>1.5</td>
<td>20 - 30</td>
<td>1 - 4</td>
<td>3 - 10</td>
</tr>
<tr>
<td>- Anthracite</td>
<td>92</td>
<td>&lt;4</td>
<td>1</td>
<td>2</td>
<td>1.5</td>
<td>10</td>
<td>1 - 4</td>
<td>3 - 10</td>
</tr>
<tr>
<td>Coke</td>
<td>98</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3 - 10</td>
</tr>
<tr>
<td>Raw brown coal</td>
<td>68</td>
<td>5</td>
<td>1</td>
<td>25</td>
<td>1</td>
<td>30</td>
<td>50</td>
<td>3 - 15</td>
</tr>
<tr>
<td>Lignite dust</td>
<td>65 - 75</td>
<td>4 - 7</td>
<td>0.2 - 1</td>
<td>15 - 25</td>
<td>0.5 - 1</td>
<td>44 - 48</td>
<td>10 - 20</td>
<td>3 - 15</td>
</tr>
<tr>
<td>Wood</td>
<td>47 - 53</td>
<td>5 - 7</td>
<td>0 - 0.3</td>
<td>42 - 46</td>
<td>0 - 0.7</td>
<td>60 - 90</td>
<td>10 - 20</td>
<td>0 - 4</td>
</tr>
</tbody>
</table>

Table 2-1: Reference values for the composition of fossil fuels
### Table 2-2: Determination of air demand of gaseous fuels

<table>
<thead>
<tr>
<th>Component</th>
<th>$v_i$ [Mol$_{O_i}$/Mol$_i$]</th>
<th>$\rho_i$ [kg$_i$/m$_i^3$]</th>
<th>$\tilde{x}_i$ [m$<em>i^3$/m$</em>{O_i}^3$]</th>
<th>$\tilde{\tilde{O}}_i$</th>
<th>$\tilde{x}_i$ [kg$<em>i$/m$</em>{O_i}^3$]</th>
<th>$\tilde{\tilde{O}}_i$</th>
<th>$\tilde{x}_i$ [kg$<em>i$/m$</em>{O_i}^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>2</td>
<td>0.705</td>
<td>0.9</td>
<td>1.8</td>
<td>0.635</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>3.5</td>
<td>1.322</td>
<td>0.03</td>
<td>0.105</td>
<td>0.040</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>CO</td>
<td>0.5</td>
<td>1.234</td>
<td>0.005</td>
<td>0.0025</td>
<td>0.006</td>
<td>0.28</td>
<td>0.14</td>
</tr>
<tr>
<td>H$_2$</td>
<td>0.5</td>
<td>0.088</td>
<td>0.005</td>
<td>0.0025</td>
<td>0.0</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0</td>
<td>1.90</td>
<td>0.03</td>
<td>0</td>
<td>0.057</td>
<td>0.1</td>
<td>0.19</td>
</tr>
<tr>
<td>N$_2$</td>
<td>0</td>
<td>1.234</td>
<td>0.03</td>
<td>0</td>
<td>0.037</td>
<td>0.6</td>
<td>0.740</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td></td>
<td></td>
<td>1</td>
<td>1.91</td>
<td>0.78</td>
<td>1</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### Table 2-3: Determination of air demand of liquid and solid fuels (daf)

<table>
<thead>
<tr>
<th>Component</th>
<th>$v_i$ [Mol$_{O_i}$/Mol$_i$]</th>
<th>$\tilde{M}_i$ [kg$_i$/kmol$_i$]</th>
<th>$x_{if}$ [kg$<em>i$/kg$</em>{O_i}$]</th>
<th>$O_{if}$ [kg$<em>i$/kg$</em>{O_i}$]</th>
<th>$x_{if}$ [kg$<em>i$/kg$</em>{O_i}$]</th>
<th>$O_{if}$ [kg$<em>i$/kg$</em>{O_i}$]</th>
<th>$x_{if}$ [kg$<em>i$/kg$</em>{O_i}$]</th>
<th>$O_{if}$ [kg$<em>i$/kg$</em>{O_i}$]</th>
<th>$x_{if}$ [kg$<em>i$/kg$</em>{O_i}$]</th>
<th>$O_{if}$ [kg$<em>i$/kg$</em>{O_i}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1</td>
<td>12</td>
<td>0.86</td>
<td>2.29</td>
<td>0.83</td>
<td>2.21</td>
<td>0.92</td>
<td>2.45</td>
<td>0.70</td>
<td>1.86</td>
</tr>
<tr>
<td>H</td>
<td>0.25</td>
<td>1</td>
<td>0.13</td>
<td>1.04</td>
<td>0.06</td>
<td>0.48</td>
<td>0.04</td>
<td>0.32</td>
<td>0.05</td>
<td>0.41</td>
</tr>
<tr>
<td>S</td>
<td>1</td>
<td>32</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>O</td>
<td>0</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0.08</td>
<td>-0.08</td>
<td>0.02</td>
<td>-0.02</td>
<td>0.25</td>
<td>-0.25</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td></td>
<td>1</td>
<td>3.34</td>
<td>0.98</td>
<td>2.62</td>
<td>1.58</td>
<td>2.76</td>
<td>2.02</td>
<td>1.94</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Table 2-2: Determination of air demand of gaseous fuels

Table 2-3: Determination of air demand of liquid and solid fuels (daf)
<table>
<thead>
<tr>
<th></th>
<th>$\tilde{M}$ [kg/kmol]</th>
<th>Vol %</th>
<th>Mas %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen $\text{N}_2$</td>
<td>28.0</td>
<td>78.1</td>
<td>75.5</td>
</tr>
<tr>
<td>Oxygen $\text{O}_2$</td>
<td>32.0</td>
<td>21.0</td>
<td>23.1</td>
</tr>
<tr>
<td>Argon $\text{Ar}$</td>
<td>40.2</td>
<td>0.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Air</td>
<td>29.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2-4: Composition of dry air

<table>
<thead>
<tr>
<th>Fuel</th>
<th>$\tilde{\Omega}$ [m$<em>{\text{o}}^{3}$/m$</em>{\text{i}}^{3}$]</th>
<th>$\Omega$ [kg$<em>{\text{o}}$/kg$</em>{\text{i}}$]</th>
<th>$\tilde{L}$ [m$<em>{\text{L}}^{3}$/m$</em>{\text{i}}^{3}$]</th>
<th>$L$ [kg$<em>{\text{L}}$/kg$</em>{\text{i}}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas H</td>
<td>1.95</td>
<td>3.91</td>
<td>9.3</td>
<td>16.9</td>
</tr>
<tr>
<td>Natural gas L</td>
<td>1.91</td>
<td>3.45</td>
<td>9.1</td>
<td>14.9</td>
</tr>
<tr>
<td>Top gas</td>
<td>0.15</td>
<td>0.16</td>
<td>0.71</td>
<td>0.71</td>
</tr>
<tr>
<td>Biogas</td>
<td>1.0 – 1.2</td>
<td>1.09 – 1.44</td>
<td>4.8 – 5.7</td>
<td>4.7 – 6.2</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>2</td>
<td>4</td>
<td>9.5</td>
<td>17.3</td>
</tr>
<tr>
<td>CO</td>
<td>0.5</td>
<td>0.57</td>
<td>2.38</td>
<td>2.47</td>
</tr>
<tr>
<td>H$_2$</td>
<td>0.5</td>
<td>8</td>
<td>2.38</td>
<td>34.5</td>
</tr>
<tr>
<td>Oil EL</td>
<td>-</td>
<td>3.34</td>
<td>-</td>
<td>14.5</td>
</tr>
<tr>
<td>Methanol</td>
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<td>1.5</td>
<td>-</td>
<td>6.47</td>
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<tr>
<td>Ethanol</td>
<td>-</td>
<td>2.09</td>
<td>-</td>
<td>9.00</td>
</tr>
<tr>
<td>Gas flame coal (daf)</td>
<td>-</td>
<td>2.62</td>
<td>-</td>
<td>11.2</td>
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<tr>
<td>Anthrazit (daf)</td>
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<td>2.76</td>
<td>-</td>
<td>12.0</td>
</tr>
<tr>
<td>Lignite dust</td>
<td>-</td>
<td>1.70</td>
<td>-</td>
<td>7.3</td>
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<tr>
<td>Wood</td>
<td>-</td>
<td>1.35 – 1.4</td>
<td>-</td>
<td>5.8 – 6.0</td>
</tr>
</tbody>
</table>

Table 2-5: Air demand of fuels
Fig. 2-1: Equilibrium numbers of several reactions

\[
\frac{\Delta G(T)}{\Delta G_0(T_0)} = 1 - m \cdot \left[ \left( \frac{T}{T_0} \right)^n - 1 \right]
\]

\[ K = \exp \left( -\frac{\Delta G(T)}{R \cdot T} \right) \]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\Delta h_0$ [kJ/mol]</th>
<th>$\Delta G_0$ [kJ/mol]</th>
<th>m</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO + H$_2$O $\Leftrightarrow$ CO$_2$ + H$_2$</td>
<td>-41.1</td>
<td>-28.6</td>
<td>0.6564</td>
<td>0.7133</td>
</tr>
<tr>
<td>H$_2$ + 1/2 O$_2$ $\Leftrightarrow$ H$_2$O</td>
<td>-241.8</td>
<td>-228.6</td>
<td>0.0614</td>
<td>1.0665</td>
</tr>
<tr>
<td>CO + 1/2 O$_2$ $\Leftrightarrow$ CO$_2$</td>
<td>-283.0</td>
<td>-257.2</td>
<td>0.1096</td>
<td>0.9592</td>
</tr>
<tr>
<td>H + OH $\Leftrightarrow$ H$_2$O</td>
<td>-498.8</td>
<td>-466.2</td>
<td>0.0724</td>
<td>1.0484</td>
</tr>
<tr>
<td>O + O $\Leftrightarrow$ O$_2$</td>
<td>-498.4</td>
<td>-463.5</td>
<td>0.0767</td>
<td>1.0374</td>
</tr>
<tr>
<td>H + H $\Leftrightarrow$ H$_2$</td>
<td>-436.0</td>
<td>-406.6</td>
<td>0.0714</td>
<td>1.0693</td>
</tr>
<tr>
<td>CO + O $\Leftrightarrow$ CO$_2$</td>
<td>-532.1</td>
<td>-488.9</td>
<td>0.0923</td>
<td>0.9988</td>
</tr>
<tr>
<td>CH$_4$ + CO$_2$ $\Leftrightarrow$ 2 H$_2$ + 2 CO</td>
<td>257.8</td>
<td>170.8</td>
<td>0.4643</td>
<td>1.0253</td>
</tr>
<tr>
<td>C + CO$_2$ $\Leftrightarrow$ 2 CO</td>
<td>172.4</td>
<td>120.0</td>
<td>0.4845</td>
<td>0.9484</td>
</tr>
<tr>
<td>C + H$_2$O $\Leftrightarrow$ CO + H$_2$</td>
<td>131.3</td>
<td>91.4</td>
<td>0.4625</td>
<td>0.9996</td>
</tr>
<tr>
<td>C + O$_2$ $\Leftrightarrow$ CO$_2$</td>
<td>-393.5</td>
<td>-394.4</td>
<td>-0.2997</td>
<td>0.0072</td>
</tr>
<tr>
<td>C + 1/2 O$_2$ $\Leftrightarrow$ CO</td>
<td>-110.5</td>
<td>-137.2</td>
<td>-0.2185</td>
<td>0.9377</td>
</tr>
</tbody>
</table>

Table 2-6: Enthalpies of reactions, free standard reaction enthalpies and constants to calculate the equilibrium numbers ($T_0 = 298.15$ K)
Fig. 2-2: Concentration for $\lambda$ around 1

Vol.-Concentration vs Excess air number

$\vartheta_g = 1800 ^\circ C$

$\vartheta_g = 1200 ^\circ C$
Fig. 2-3: Composition of flue gas of natural gas type L

Fig. 2-4: Composition of combustion gas of natural gas type L
Fig. 2-5: Composition of combustion gas of fuel oil (light)

Fig. 2-6: Composition of combustion gas of typical fuels
Fig. 2.7: Specific amount of combustion gas

Fig. 2.8: Normal density of combustion gas
Fig. 2-9: Composition of combustion gas for $\lambda < 1$

Fig. 2-10: Combustion gas humidity
Fig. 2-11: Combustion gas dew point temperature