| Fuel/Oxidizer Mixing	Fluid Motion	Examples
premixed	turbulent	spark-ignited gasoline engine low NO$_x$ stationary gas turbine
	laminar	flat flame Bunsen flame (followed by a nonpremixed candle for $\Phi > 1$)
nonpremixed	turbulent	pulverized coal combustion aircraft turbine Diesel engine H$_2$/O$_2$ rocket motor
	laminar	wood fire radiant burners for heating candle

In combustion processes, fuel and oxidizer (typically air) are mixed and burned. It is useful to identify several combustion categories based upon whether the fuel and oxidizer is mixed first and burned later (*premixed*) or whether combustion and mixing occur simultaneously (*nonpremixed*). Each of these categories is further subdivided based on whether the fluid flow is laminar or turbulent. Table 1.2 shows examples of combustion systems that belong to each of these categories, which will be discussed in the following sections.

Laminar Premixed Flames: In *laminar premixed flames*, fuel and oxidizer are premixed before combustion and the flow is laminar. Examples are laminar *flat flames* and (under fuel-lean conditions) *Bunsen flames* (see Fig. 1.1).
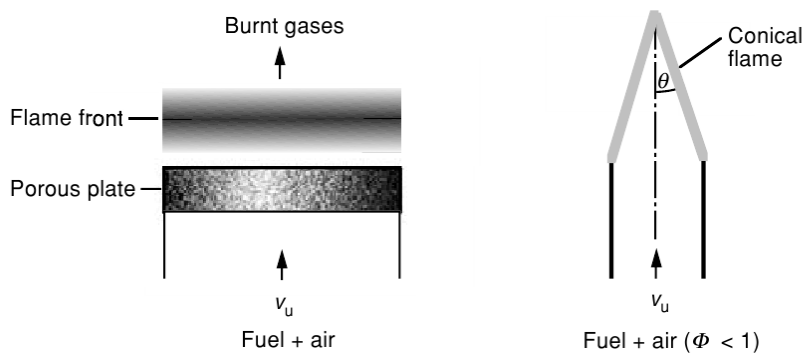
A premixed flame is said to be *stoichiometric*, if fuel (e. g., a hydrocarbon) and oxidizer (e. g., oxygen O_2) consume each other completely, forming only carbon dioxide (CO_2) and water (H_2O). If there is an excess of fuel, the system is called *fuel-rich*, and if there is an excess of oxygen, it is called *fuel-lean*. Examples are

$$
\begin{array}{llll}
2\ H_2 & + & O_2 & \rightarrow & 2\ H_2O & & \text{stoichiometric} \\
3\ H_2 & + & O_2 & \rightarrow & 2\ H_2O\ +\ H_2 & & \text{rich (H_2 left over)} \\
& CH_4 & +\ 3\ O_2 & \rightarrow & 2\ H_2O\ +\ CO_2\ +\ O_2 & & \text{lean (O_2 left over).}
\end{array}
$$
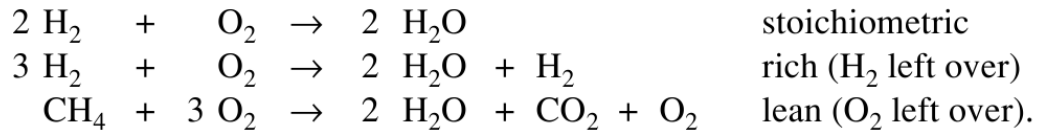
Each species symbol in such a chemical reaction equation represents 1 mol. Thus, the first equation means: 2 mol H_2 react with 1 mole O_2 to form 2 mole H_2O.

If the reaction equation is written such that it describes exactly the reaction of 1 mol fuel, the mole fraction of the fuel in a stoichiometric mixture can be calculated easily to be

$$
x_{\text{fuel,stoich.}} = \frac{1}{1+v} . \tag{1.6}
$$

Here v denotes the number of moles of O_2 in the reaction equation for a complete reaction to CO_2 and H_2O. An example is

$$
H_2 + 0.5\,O_2 \rightarrow H_2O \qquad v = 0.5 \qquad x_{H_2,\text{stoich.}} = 2/3.
$$

If air is used as an oxidizer, it has to be taken into account that dry air contains only about 21 % oxygen (78% nitrogen, 1% noble gases). Thus, for air $x_{N_2} = 3.762\,x_{O_2}$. It follows that the mole fractions in a stoichiometric mixture with air are

$$
x_{\text{fuel,stoich.}} = \frac{1}{1+v\cdot 4.762}, \ x_{O_2,\text{stoich.}} = v\cdot x_{\text{fuel,stoich.}}, \ x_{N_2,\text{stoich.}} = 3.762\cdot x_{O_2,\text{stoich.}} \tag{1.7}
$$

v denotes, again, the mole number of O_2 in the reaction equation for a complete reaction of 1 mol of fuel to CO_2 and H_2O. Some examples are given in Table 1.3.

Tab. 1.3. Examples of stoichiometric numbers v and of fuel mole fractions at stoichiometric conditions $x_{\text{fuel, stoich}}$ in fuel/air mixtures

Reaction		v	$x_{\text{fuel, stoich.}}$
H_2 $+$ $0.5\,O_2$ $+$ $0.5\cdot3.762\,N_2$ $\rightarrow$	H_2O $+$ $0.5\cdot3.762\,N_2$	0.5	29.6 mol-%
CH_4 $+$ $2.0\,O_2$ $+$ $2.0\cdot3.762\,N_2$ $\rightarrow$	CO_2 $+$ $2\,H_2O$ $+$ $2.0\cdot3.762\,N_2$	2.0	9.50 mol-%
C_3H_8 $+$ $5.0\,O_2$ $+$ $5.0\cdot3.762\,N_2$ $\rightarrow$	$3\,CO_2$ $+$ $4\,H_2O$ $+$ $5.0\cdot3.762\,N_2$	5.0	4.03 mol-%
C_7H_{16} $+11.0\,O_2$ $+11.0\cdot3.762\,N_2$ $\rightarrow$	$7\,CO_2$ $+$ $8\,H_2O$ $+11.0\cdot3.762\,N_2$	11.0	1.87 mol-%
C_8H_{18} $+12.5\,O_2$ $+12.5\cdot3.762\,N_2$ $\rightarrow$	$8\,CO_2$ $+$ $9\,H_2O$ $+12.5\cdot3.762\,N_2$	12.5	1.65 mol-%

Premixtures of fuel and air (the proper amount of N_2 has to be added in this case on both sides of the reaction equation; see Table 1.3) are characterized by the *air equivalence ratio* (sometimes *air number*) or the reciprocal value, the *fuel equivalence ratio* $\Phi = 1/\lambda$ with

$$\lambda = (x_{\text{air}}/x_{\text{fuel}}) \,/\, (x_{\text{air,stoich.}}/x_{\text{fuel, stoich.}}) = (w_{\text{air}}/w_{\text{fuel}}) \,/\, (w_{\text{air,stoich.}}/w_{\text{fuel, stoich.}}) \,.$$

This formula can be rewritten to allow the evaluation of mole fractions in a mixture from Φ by

$$x_{\text{fuel}} = \frac{1}{1+\dfrac{4.762\cdot v}{\Phi}} \;,\; x_{\text{air}} = 1-x_{\text{fuel}} \;,\; x_{O_2} = x_{\text{air}}/4.762 \;,\; x_{N_2} = x_{O_2}\cdot3.762 \,.$$

Accordingly, premixed combustion processes can now be divided into three groups,

rich combustion:	$\Phi > 1$,	$\lambda < 1$
stoichiometric combustion:	$\Phi = 1$,	$\lambda = 1$
lean combustion:	$\Phi < 1$,	$\lambda > 1$.

The burning of freely burning premixed laminar flat flames into the unburnt mixture can be characterized by the *laminar burning velocity* v_L (e. g., in m/s); other names in the literature are *flame velocity* or *flame speed*. It will be shown in Chapter 8 that the burning velocity depends only on the mixture composition (Φ or λ), the pressure p, and the initial temperature T_u.

   If the laminar burning velocity of a flat flame is less than the velocity v_u of the unburnt gases (see Fig. 1.1), the flame blows off. Therefore, the inequality $v_L > v_u$

has to be fulfilled for flat flames. Right before the blowoff $v_L \approx v_u$. Thus, the inlet gas velocity at flame lift-off is a measure of the laminar burning velocity.

Higher inlet velocities are possible when the flat flame is at an angle θ to the flow. In the case of a premixed Bunsen flame attached to the exit of a round pipe, the flame front is approximately flat (the flame thickness is small compared to the curvature). It follows (see Fig. 1.1) that

$$v_L = v_u \sin \theta. \tag{1.8}$$

Thus, a measurement of θ, perhaps from a photograph, and of the inlet gas velocity v_u will lead to a measure of v_L. Problems connected with the determination of v_L and better experimental methods are discussed by Vagelopoulos and Egolfopoulos (1998).