

FUNDAMENTAL COMBUSTION TECHNOLOGY

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Abstract. The purpose of this paper is to demonstrate the fundamental principles of combustion technology. After a short review on the physics and chemistry of flames the different types of flames and combustion modes are described. Diffusion flames as they are used in propulsion systems are discussed in detail. Thereby the main stress of the discussion is laid on the influence of large scale turbulent structures on the fuel/air mixing process, the mechanism of flame stabilization and the structure and behaviour of diffusion flames. Results of experimental investigations in sub- and supersonic hydrogen/air flames underpin the theoretical predictions.

Keywords: physics and chemistry of flames – turbulent combustion – mixing – flame stabilization – hydrogen/air flames

1. Introduction and basic phenomena in combustion

Combustion is still the most common way to generate thrust in propulsion systems for aeronautic and space application. The basic intention of this paper is point out what combustion is and how combustion processes can be handled. This is an important factor for the design of modern propulsion systems especially concerning a high performance ratio coupled with a low environmental impact.

In general it can be said that combustion means the conversion of chemically stored energy into thermal energy. In propulsion systems this thermal energy can be converted into kinetic energy by means of thrust nozzles. Combustion is defined as an exothermal chemical process in which a combustible or fuel is oxidized. Fuels such as methane or kerosine are pure chemical substances or mixtures of chemical substances with a high content of bonding energy which can undergo an oxidization process. In general fuels consist of combustible species like carbon (C), hydrogen (H), sulfur (S), boron (B), beryllium (Be), aluminum (Al), lithium (Li), nitrogen (N) and magnesium (Mg) and of uncombustible species like oxygen (O), chlorine (Cl) and fluorine (F). Examples of pure substances used as fuels are molecular hydrogen (H_2), methane (CH_4), ethanol (C_2H_5OH) and hydrazine (N_2H_4). Fuel mixtures of pure substances are for example kerosine, diesel oil and nitrocellulosis + nitroglycerine. More examples of propellants are given by Münzberg (1972), Urlaub (1991), Strehlow (1984) and Kuo (1986).

The most common oxydizer used in combustion systems is molecular oxygen (O_2). It can supplied as a pure substance, as liquid oxygen (LOX) or as a component of the air. Another possibility to provide oxygen is by means of chemical substances like $N_2H_4O_2$. Other oxydizers are in very small quantities nitrogen (N) and, for rocket propellants, pure fluorine (F) or fluorine containing substances like N_2F_4 and chlorine (Cl).

In the course of the combustion process, fuel and oxydizer are combined to so called reaction products. Each component of the fuel like carbon, hydrogen, boron, sulfur or nitrogen is oxydized to a specific reaction product like CO_2 , H_2O , B_2O_3 , SO_x or NO_x . If the reaction is uncomplete due to insufficient mixing or quenching effects, other additional reaction products like CO or unburned hydrocarbon (CH) may occur. Chapter 2 of this paper provides analytical formulae how the demand of oxydizer and the amount of reaction products per unit fuel can be calculated in detail.

To start the reaction of a fuel/oxydizer mixture, it must be initiated by increasing the energy level of the participating molecules. The initial energy for this energy increase is called activation energy and the process is called ignition. In most of the technical applications the increase of the energy level is obtained by increasing the initial gas temperature up to the so called ignition temperature. Lewis and

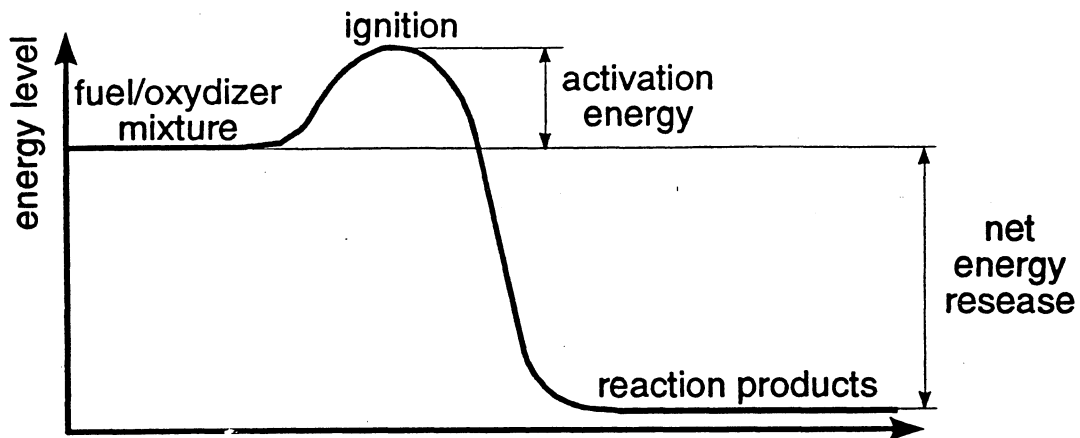


Fig. 1. Distribution of the different energy levels in combustion processes

v. Elbe (1951) listed data of the ignition temperature for a number of fuel/oxydizer mixtures. Figure 1 shows schematically the different energy levels of an unburned fuel/oxydizer mixture, of the activated combustibles and of the reaction products. Detailed information on the net heat which is released during the combustion process per unit fuel and on the calculation of maximum available flame temperature will be provided in chapter 2 of this paper.

As the complete chemical reaction in combustion processes presume an ideal distribution of the reactants, one has to ensure that fuel and oxydizer molecules are very well mixed before. Beyond this the unburned mixture of the reactants must be heated up to ignition temperature. Therefore transport processes in the vicinity of the reaction front like mass diffusion, thermal conductivity and convective heat and mass transfer are of great importance for the combustion process or even controll it. For example the burning velocity of a hydrogen/air flame can be varied within three orders of magnitude only by varying the heat and mass transfer parameters (Brehm (1989), Haibel (1991)).

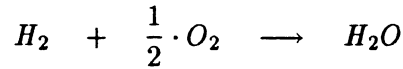
In general two different types of flames depending on the initial spacial distribution of the reactants can be distinguished, premixed flames and diffusion flames. In the former type of flame the reactants enter the combustion chamber already as a combustible mixture. Typical examples for premixed flames in propulsion systems are solid propellants as they are used in rocket engines. Diffusion flames are thereby characterized, that fuel and oxydizer enter the combustion chamber separately and are mixed during the combustion process. They are the most common type of flame in propulsion systems i.e. liquid fueled rocket engines and all kinds of jet engines like RAM-jets or SCRAM-jets (SCRAM-jet: Supersonic Combustion RAM-jet). A number of problems must be solved when handling diffusion flames like the storage, injection and mixing of fuel and oxydizer, the safe and reliable stabilization of the flames and the combustion efficiency. More detailed information on these subjects will be given in the upcoming chapters of this paper.

2. Short introduction to the physics and chemistry of flames

2.1. BASIC CHEMICAL REACTIONS

As already mentioned in chapter 1 of this paper, each type of fuel consists of elements like carbon (C), sulfur (S), hydrogen (H) and so on. The most common type of oxydizer is oxygen (O_2), either pure as liquid oxygen (LOX) or as part of an oxygen carrier like air. In some very special applications like solid fueled rockets chlorine (Cl) or fluorine (F) are used as oxydizers.

The most simple chemical reaction is the oxydation of hydrogen by means of molecular oxygen. The overall reaction equation can be written as

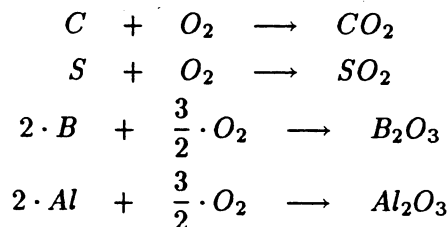


Looking at the hydrogen/oxygen reaction in detail shows, that there are 21 single reaction steps for the generation of H_2O . In table I all the single reaction steps are listed.

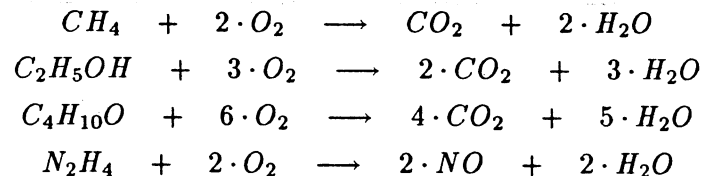
TABLE I
Single reaction steps of the overall hydrogen/oxygen reaction

1.	$H_2 + O_2$	\rightleftharpoons	$HO_2 + H$	12.	$H + O + M$	\rightleftharpoons	$OH + M$
2.	$H_2 + M$	\rightleftharpoons	$2 H + M$	13.	$H + OH + M$	\rightleftharpoons	$H_2O + M$
3.	$O_2 + M$	\rightleftharpoons	$2 O + M$	14.	$H_2O + O$	\rightleftharpoons	$2 OH$
4.	$H_2 + O$	\rightleftharpoons	$H + OH$	15.	$2 OH + M$	\rightleftharpoons	$H_2O_2 + M$
5.	$H_2 + OH$	\rightleftharpoons	$H_2O + H$	16.	$H_2O_2 + OH$	\rightleftharpoons	$HO_2 + H_2O$
6.	$H_2 + HO_2$	\rightleftharpoons	$H_2O_2 + H$	17.	$H + H_2O_2 + M$	\rightleftharpoons	$OH + H_2O + M$
7.	$H + O_2$	\rightleftharpoons	$OH + O$	18.	$H + HO_2$	\rightleftharpoons	$H_2O + O$
8.	$H + O_2 + M$	\rightleftharpoons	$HO_2 + M$	19.	$H_2 + O_2$	\rightleftharpoons	$2 OH$
9.	$H_2O + O_2$	\rightleftharpoons	$HO_2 + OH$	20.	$HO_2 + O$	\rightleftharpoons	$OH + O_2$
10.	$H_2O_2 + O_2$	\rightleftharpoons	$2 HO_2$	21.	$H_2 + HO_2$	\rightleftharpoons	$OH + H_2O$
11.	$HO_2 + H$	\rightleftharpoons	$2 OH$				

The knowledge about the single reaction steps is significant for the determination of the reaction time, the reaction rate concerning dissoziation-recombination effects, and the burning velocity. More information on this is provided by e.g. Kuo (1986) and Strehlow (1984). To calculate the fundamental combustion parameters which are important for combustion chamber design like the demand of oxygen and air, the amount of reaction products or the maximum flame temperature the overall reaction equation is sufficient to know. Other important combustion reactions of single species are the oxydation of carbon, sulfur, boron and aluminum.



The chemical reaction of homogenous types of fuel like methane or ethanol can be set up in the same way as for single elements.

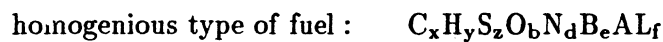


Heterogenous types of fuel like kerosine or many solid propellants can be handled as a mixture of pure substances. Therefore no single overall reaction equation for these types of fuels can be raised. The chemical reaction equation for these combustibles is the sum of single reaction equations of all participating species or pure fuels. It must be considered, that the overall reaction velocity for heterogenous fuels is limited by the most slowly single reaction step.

2.2. DEMAND OF OXYGEN AND AIR

One of the basic factors for combustion chamber design is the demand of oxygen to burn the fuel completely. This is an important information not only for the determination of the size of the combustion chamber but also for the size of the inlet cross section of airbreathing propulsion systems or the size of oxygen storage bunkers for rocket engines respectively. Depending on the type of fuel there are two ways to calculate the minimum demand of oxygen concerning the stoichiometric and complete combustion of the fuel. The first way can be used if the utilized fuel is a homogenous one (e.g. methane), the second one can be used for heterogenous types of fuel (e.g. kerosine).

2.2.1. Demand of oxygen for homogenous types of fuel: The general chemical formula of a homogenous fuel containing all the combustables species mentioned in chapter 1 of the paper can be written as follows:



The subscripts are the number of atoms of each single element:

x:	number of carbon atoms in the fuel
y:	number of hydrogen atoms in the fuel
z:	number of sulfur atoms in the fuel
b:	number of oxygen atoms in the fuel
d:	number of nitrogen atoms in the fuel
e:	number of boron atoms in the fuel
f:	number of aluminum atoms in the fuel

Therewith the minimum molare demand of oxygen $O_{min,m}$ for the stoichiometric combustion can be calculated:

$$O_{min,m} = x + \frac{y}{4} + z - \frac{b}{2} + \frac{3e}{4} + \frac{3f}{4} \quad \text{in} \quad \left[\frac{\text{kmol } O_2}{\text{kmol fuel}} \right]$$

This formula neglects the consumption of oxygen by NO -, NO_2 - and N_2O -production. This simplification is admissible as NO_x is only produced in the order of parts per million (ppm) and therefore effects the minimum demand of oxygen very little.

The following example demonstrates, how the above formula is used.

Minimum demand of oxygen for the combustion of pure ethanol C_2H_5OH : $x=2$, $y=5+1=6$, $z=0$, $b=1$, $d=0$, $e=0$, $f=0$.

$$\begin{aligned} O_{min,m,ethanol} &= x + \frac{y}{4} + z - \frac{b}{2} + \frac{3e}{4} + \frac{3f}{4} = \\ &= 2 + \frac{6}{4} + 0 - \frac{1}{2} + \frac{0}{4} + \frac{0}{4} = 3 \quad \left[\frac{\text{kmol } O_2}{\text{kmol ethanol}} \right] \end{aligned}$$

2.2.2. Demand of oxygen for heterogenous types of fuel: To determine the minimum demand of oxygen for heterogenous types of fuel, the mass fractions of the fuel for each single element like carbon, hydrogen, sulfur, etc. must be known. The mass fractions are named as follows:

c:	mass fraction of carbon in the fuel given	in [kg C/kg fuel]
h:	mass fraction of hydrogen in the fuel given	in [kg H ₂ /kg fuel]
s:	mass fraction of sulfur in the fuel given	in [kg S/kg fuel]
o:	mass fraction of oxygen in the fuel given	in [kg O ₂ /kg fuel]
n:	mass fraction of nitrogen in the fuel given	in [kg N ₂ /kg fuel]
b:	mass fraction of boron in the fuel given	in [kg B/kg fuel]
al:	mass fraction of aluminum in the fuel given	in [kg Al/kg fuel]
with		
c + h + s + o + n + b + al = 1		

Therewith the minimum demand of oxygen per mass unit fuel can be calculated as:

$$o_{min} = \frac{c}{12} + \frac{h}{4} + \frac{s}{32} - \frac{o}{32} + \frac{3b}{44} + \frac{al}{36} \text{ in } \left[\frac{\text{kmol } O_2}{\text{kg fuel}} \right]$$

The following example demonstrates the application of this formula.

The minimum demand of oxygen for the complete combustion of kerosine. The mass fractions of kerosine are c=0.865, h=0.132, s=0.001, o=0.001, n=0.001, b=al=0.

$$\begin{aligned} o_{min, kerosine} &= \frac{c}{12} + \frac{h}{4} + \frac{s}{32} - \frac{o}{32} + \frac{3b}{44} + \frac{al}{36} = \\ &= \frac{0.865}{12} + \frac{0.132}{4} + \frac{0.001}{32} - \frac{0.001}{32} + \frac{0}{44} + \frac{0}{36} = \\ &= 0.10508 \left[\frac{\text{kmol } O_2}{\text{kg kerosine}} \right] \end{aligned}$$

Many applications, especially airbreathing propulsion systems, do not require pure oxygen for the combustion process but air as oxygen carrier. Knowing the composition of the air in terms of molare fractions or partial pressures, the minimum demand of air a_{min} or the minimum molare demand of air $A_{min,m}$ can be written as follows:

$$\begin{aligned} a_{min} &= \frac{o_{min}}{\gamma_{O_2,air}} \left[\frac{\text{kmol air}}{\text{kg fuel}} \right] \\ A_{min,m} &= \frac{O_{min,m}}{\gamma_{O_2,air}} \left[\frac{\text{kmol air}}{\text{kmol fuel}} \right] \end{aligned}$$

Thereby $\gamma_{O_2,air}$ is the molare fraction of oxygen in the air. At sea level the molare fraction of oxygen in the atmospheric air is 0.21. To ensure the complete combustion of all the injected fuel in the combustion chamber and to decrease the total temperature of the flame, more than the minimum demand of oxygen or air is used for the combustion process. The equivalent ratio λ of oxygen and air is defined as:

$$\lambda = \frac{o_{available}}{o_{min}} = \frac{O_{available,m}}{O_{min,m}}$$

When talking about a stoichiometric fuel/oxygen mixture λ is equal to 1. $\lambda < 1$ indicates a fuel rich mixture and $\lambda > 1$ a lean mixture.

2.3. REACTION PRODUCTS

The knowledge about the kind and quantity of the combustion products is very important for the design of propulsion systems and for the assessment of the environmental impact. To give a very simple formula to calculate the total amount of exhaust gases the following assumptions are necessary. The combustion process is complete, so that there are no unburned hydrocarbons, no soot and no carbon monoxide in the exhaust gas. The formation of nitric oxides are neglected due to their tiny quantity, and the air consists only of oxygen, nitrogen and water vapor.

The chemical reaction of a homogenous type of fuel with air can be written in the most general form as:



The sum of all reaction products like CO_2 , H_2O , SO_2 , O_2 , N_2 , B_2O_3 and Al_2O_3 is a superposition of the single reactions of the different elements taking into account the equivalent ratio λ :

$$\begin{aligned} \sum \frac{\text{exhaust gas}}{\text{mol unit fuel}} = \frac{n_{eg}}{n_F} &= x + \left(\frac{y}{2} + \lambda \cot \gamma_{H_2O,air} \cdot \frac{O_{min,m}}{\gamma_{O_2,air}} \right) + z + (\lambda - 1) \cdot O_{min,m} + \\ &+ \left(\frac{d}{2} + \lambda \cdot \gamma_{N_2,air} \cdot \frac{O_{min,m}}{\gamma_{O_2,air}} \right) + \frac{e}{2} + \frac{f}{2} \left[\frac{\text{kmol exhaust gas}}{\text{kmol fuel}} \right] \end{aligned}$$

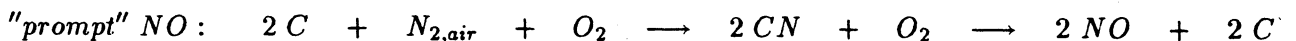
The sum of all reaction products for heterogenous types of fuel can be generally written as:

$$\begin{aligned} \sum \frac{\text{exhaust gas}}{\text{mass unit fuel}} = \frac{n_{eg}}{M_F} &= \frac{c}{12} + \left(\frac{h}{2} + \lambda \cdot \gamma_{H_2O,air} \cdot \frac{o_{min}}{\gamma_{O_2,air}} \right) + \frac{s}{32} + (\lambda - 1) \cdot o_{min} + \\ &+ \left(\frac{n}{28} + \lambda \cdot \gamma_{N_2,air} \cdot \frac{o_{min}}{\gamma_{O_2,air}} \right) + \frac{b}{22} + \frac{al}{54} \left[\frac{\text{kmol exhaust gas}}{\text{kg fuel}} \right] \end{aligned}$$

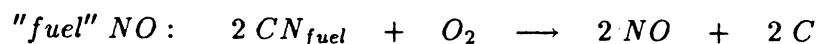
The formation of nitric oxide (NO_x) can be neglected for the calculation of the demand of oxygen and the overall amount of the exhaust gases, as the quantity is only in the order of ppm. But as NO and NO_2 are very toxic, they can not be neglected with respect to environmental considerations. Three ways of NO formation are known: "thermal" NO formation, "prompt" NO formation and "fuel" NO formation. Thermal NO is generated out of excited nitrogen from the air and excited oxygen at temperatures above 1500 K.



The production rate of NO increases with increasing temperature. Thermal NO can only be avoided by avoiding nitrogen in the combustion chamber. For the generation of "prompt" NO the first step is the formation of cyanides (CN) out of carbon and nitrogen delivered by the air. In the next reaction step the carbon atoms pass the nitrogen atoms to an oxygen atom.



The carbon atoms act in this reaction as a kind of catalyst. In some organic types of fuels like oil or wood, cyanides are already part of the fuel. In this case the cyanides are directly converted into NO .



The formation of "fuel" NO and of "prompt" NO takes place at lower temperatures but higher production rates as the formation of "thermal" NO . More information on this topic and on the NO_2 formation by quenching mechanisms of NO is given by Morley (1981), Fenimore (1971), Blauwens et al. (1977), Leuckel (1985), Peters (1981) and Hori (1988).

2.4. HEAT OF REACTION

The energy chemically stored in the fuel molecules and which is set free during the combustion process is called heat of reaction. Depending on the type of fuel, the unit of the heat of reaction (or the reaction enthalpy) is given in [kJ/kmol fuel] or [kJ/kg fuel]. In the upcoming table II the heat of reaction of some fuels are listed.

 TABLE II
Heat of reaction

fuel:	heat of reaction:	
H_2	241,700	$\left[\frac{\text{kJ}}{\text{kmol}} \right]$
C	406,800	$\left[\frac{\text{kJ}}{\text{kmol}} \right]$
CH_4	802,700	$\left[\frac{\text{kJ}}{\text{kmol}} \right]$
C_3H_8	2,045,100	$\left[\frac{\text{kJ}}{\text{kmol}} \right]$
coal	31,000	$\left[\frac{\text{kJ}}{\text{kg}} \right]$
kerosine	42,900	$\left[\frac{\text{kJ}}{\text{kg}} \right]$

Using the heat of reaction and the energy conservation law (1st. law of thermodynamics) the maximum adiabatic flame temperature t_{max} can be calculated.

$$t_{max} = \frac{\Delta H_{m,F} + c_{p,m,F} \cdot t_F + \lambda \cdot \frac{O_{min,m}}{\gamma_{O_2,air}} \cdot c_{p,m,air} \cdot t_{air}}{\sum_i \frac{n_{i,eg}}{n_F} \cdot c_{p,m,i,eg} |^{t_{max}}}$$

Thereby t_{max} is the maximum adiabatic flame temperature in [$^{\circ}C$], $c_{p,m,i,eg} |^{t_{max}}$ the molare heat capacity of each single component i of the exhaust gas at the temperature t_{max} , t_f and t_{air} the initial temperatures of the fuel and the air in [$^{\circ}C$] and $\Delta H_{m,F}$ the lower molare heat of reaction of the fuel. It can be seen that the equation has to be solved via iteration as the molare heat capacity of the reaction products are functions of the maximal flame temperature. The following example shows how the maximum adiabatic flame temperature can be calculated.

A combustion chamber is fired with a stoichiometric mixture ($\lambda=1$) of methane (CH_4) and air ($\gamma_{O_2,air}=0.21$; $\gamma_{N_2,air}=0.79$). The initial temperature of the incoming air and fuel is $0^{\circ}C$ ($t_F = t_{air} = 0^{\circ}C$). The maximum adiabatic flame temperature t_{max} is calculated as follows:

$$\begin{aligned} t_{max} &= \frac{\Delta H_{m,CH_4} + c_{p,m,CH_4} \cdot t_F + \lambda \cdot \frac{O_{min,m}}{\gamma_{O_2,air}} \cdot c_{p,m,air} \cdot t_{air}}{\sum_i \frac{n_{i,eg}}{n_F} \cdot c_{p,m,i,eg} |^{t_{max}}} \\ &= \frac{\Delta H_{m,CH_4} + c_{p,m,CH_4} \cdot t_F + \lambda \cdot \frac{O_{min,m}}{\gamma_{O_2,air}} \cdot c_{p,m,air} \cdot t_{air}}{\frac{n_{CO_2}}{n_{CH_4}} \cdot c_{p,m,CO_2} |^{t_{max}} + \frac{n_{H_2O}}{n_{CH_4}} \cdot c_{p,m,H_2O} |^{t_{max}} + \frac{O_{min,m}}{\gamma_{O_2,air}} \cdot \gamma_{N_2,air} \cdot c_{p,m,N_2} |^{t_{max}}} \\ &= \frac{802,707}{1 \cdot c_{p,m,CO_2} |^{t_{max}} + 2 \cdot c_{p,m,H_2O} |^{t_{max}} + 7.5 \cdot c_{p,m,N_2} |^{t_{max}}} \end{aligned}$$

→ iteration :

$$t_{max} = 2,037^{\circ}C$$

2.5. TYPES OF FLAMES AND COMBUSTION MODES

Up to now it was presumed, that in very state of the chemical reaction the participating reactants are macroscopically and microscopically well mixed and that the energy level is high above the ignition temperature. In technical furnaces and propulsion systems this assumptions are not automatically fulfilled. Therefore two types of flames can be distinguished, premixed flames and non-premixed flames. The preheating of the unburned fuel/oxydizer mixture up to ignition temperature can be obtained either by

convective heat and mass transfer from the hot exhaust gases to the cold unburned mixture or by strong shock waves. In the following the different types of flames and combustion modes are described in detail.

2.5.1. Premixed flames: If the fuel and the oxygen carrier are mixed well before entering the combustion chamber, the upcoming flame is called premixed. Examples where this types of flame occur are car engines (not diesel!) and rockets fired with solid propellants. To get a better understanding what happens in a premixed flame, figure 2 shows the model of the flame front (i.e. reaction front) of a laminar premixed flame (e.g. hydrogen/air flame).

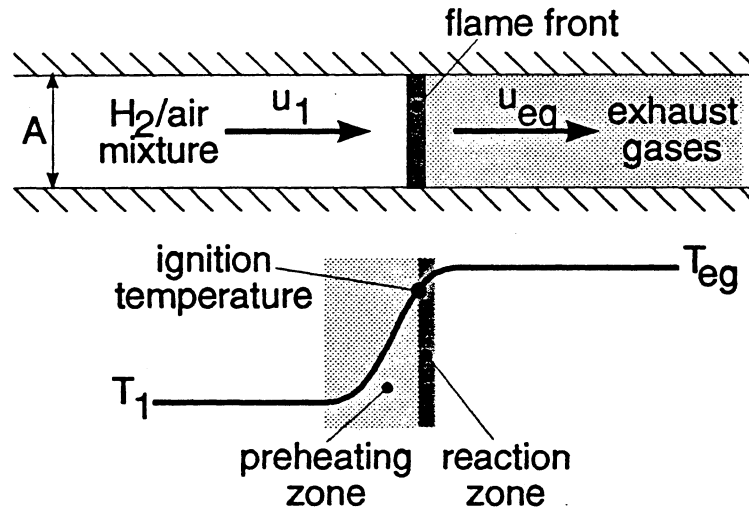


Fig. 2. Model of the flame front of a laminar premixed hydrogen/air flame with the indicated temperature profile in the different flame zones

Figure 2 illustrates that the cold unburned hydrogen/air mixture has to be preheated up to ignition temperature by means of thermal conductivity and convective heat transfer first. After reaching the ignition temperature the combustion process starts and the temperature increases further up to the adiabatic flame temperature. If u_1 is the velocity of the unburned hydrogen/air mixture and the cross section of the flame front A is identical with the cross section of the tube (i.e. smooth flame front), the propagation velocity of the flame front and thereby the burning velocity of the flame u_B must be equal to u_1 presuming a stationary flame.

$$u_1 = u_B =: s_L$$

In this case where the reaction front is smooth the burning velocity u_B is called the laminar burning velocity s_L . The laminar burning velocity is a property only depending on type of fuel and oxydizer, on the equivalent ratio of the mixture and on the initial pressure and temperature of the mixture. Some examples of laminar burning velocities are listed in table III.

When increasing the flow velocity u_1 of the unburned fuel/oxydizer mixture the reaction front of the flame will be wrinkled by means of macroscopic turbulent structures (fig. 3). This effects that the area of the turbulent flame front A_T increases. As the burning direction of the flame is always normal to the reaction front surface with the laminar burning velocity s_L , the effective burning velocity of the turbulent flame can be described by using the conservation law of mass:

$$u_1 = u_B = s_L \cdot \frac{A_T}{A}$$

This means that by inducing macroscopic turbulent structures to the flow of the fuel/oxydizer mixture the effective burning velocity of the flame can be enhanced. Experiments have shown that turbulence

TABLE III
examples of laminar burning velocities s_L at stoichiometry and at standard conditions for pressure and temperature

fuel/oxydizer mixture	s_L in $\left[\frac{m}{s}\right]$
$H_2 + \text{air}$	1.8
$H_2 + O_2$	10
$CH_4 + \text{air}$	0.35
$CH_4 + O_2$	1.8

accelerates the flame propagation velocity of the premixed hydrogen/air up to two orders of magnitude (Brehm (1988), Mayinger (1991), Haibel (1991)).

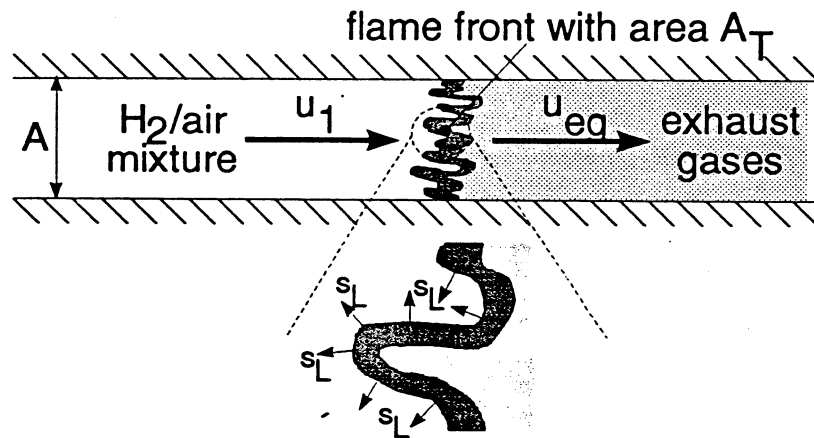


Fig. 3. Model of the wrinkled flame front of a turbulent premixed hydrogen/air flame

Two different kinds of combustion modes in premixed flames can be distinguished depending on the way how the unburned fuel/oxydizer mixture is preheated up to ignition temperature: deflagration and detonation. In deflagrations the mixture is preheated by means of turbulent heat and mass transport and by thermal conductivity. This means that there is a heat transfer from the hot reaction products to the cold mixture. Large scale turbulent structures enhance this heat transfer and increases the effective burning velocity of the flame. In detonations the mixture is preheated by strong shock waves right in front of the reaction zone. As shock waves propagate very fast the flame front, velocities are very fast too (more than 2000 m/s in stoichiometric hydrogen/air mixtures). Figure 4 shows the model of a deflagrative and a detonative reaction front.

There is a third combustion mode which is partly controlled by convective heat and mass transfer and by a weak shock wave. This mode is called supersonic flame (Brehm (1988), Mayinger (1991)). Experiments have shown that this combustion mode can be used to stabilize flames in SCRAM-jet engines at high Mach number (Algermissen (1970), Kasal (1989), Menon (1989)).

Figure 5 shows the different combustion modes of a premixed hydrogen/air flame recorded in an explosion tube. The tube was partly provided with turbulence promoters to accelerate the flames. It can be seen that with increasing equivalent ratio of hydrogen and air the velocity of the flame front increases from 500 m/s (deflagration) up to 1800 m/s (detonation). It can be seen further that the turbulence promoting obstacle in the first half of the explosion tube accelerate the flame front tremendously.

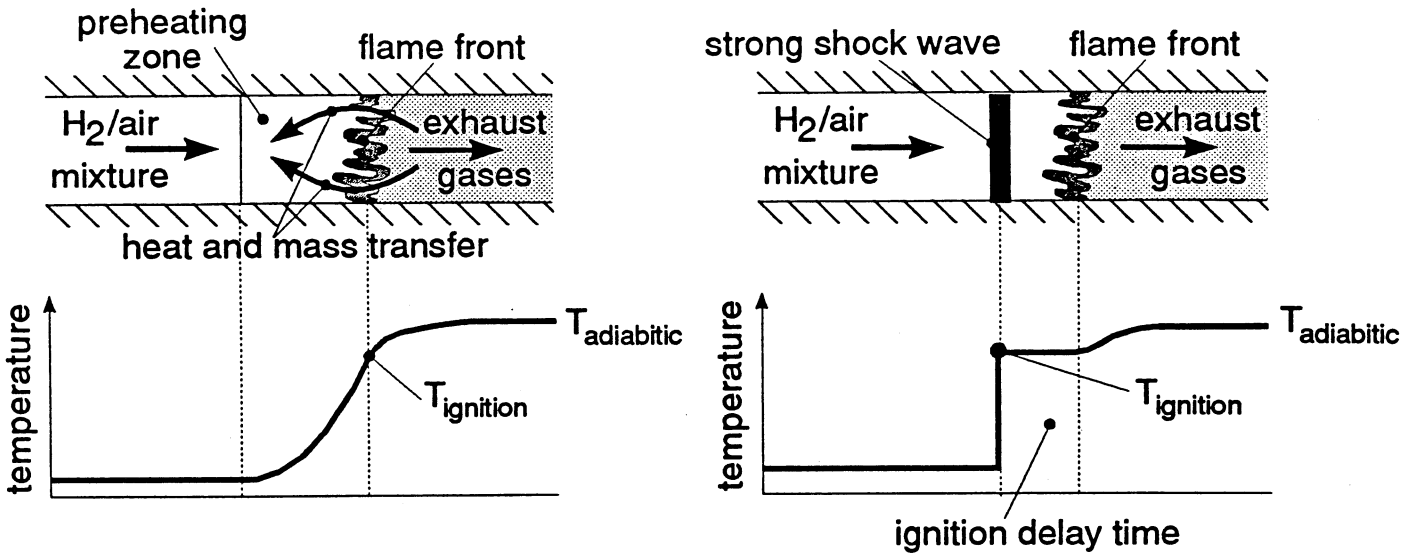


Fig. 4. Model of a deflagrative (left) and a detonative (right) reaction front of a premixed hydrogen/air flame with the temperature profiles indicated

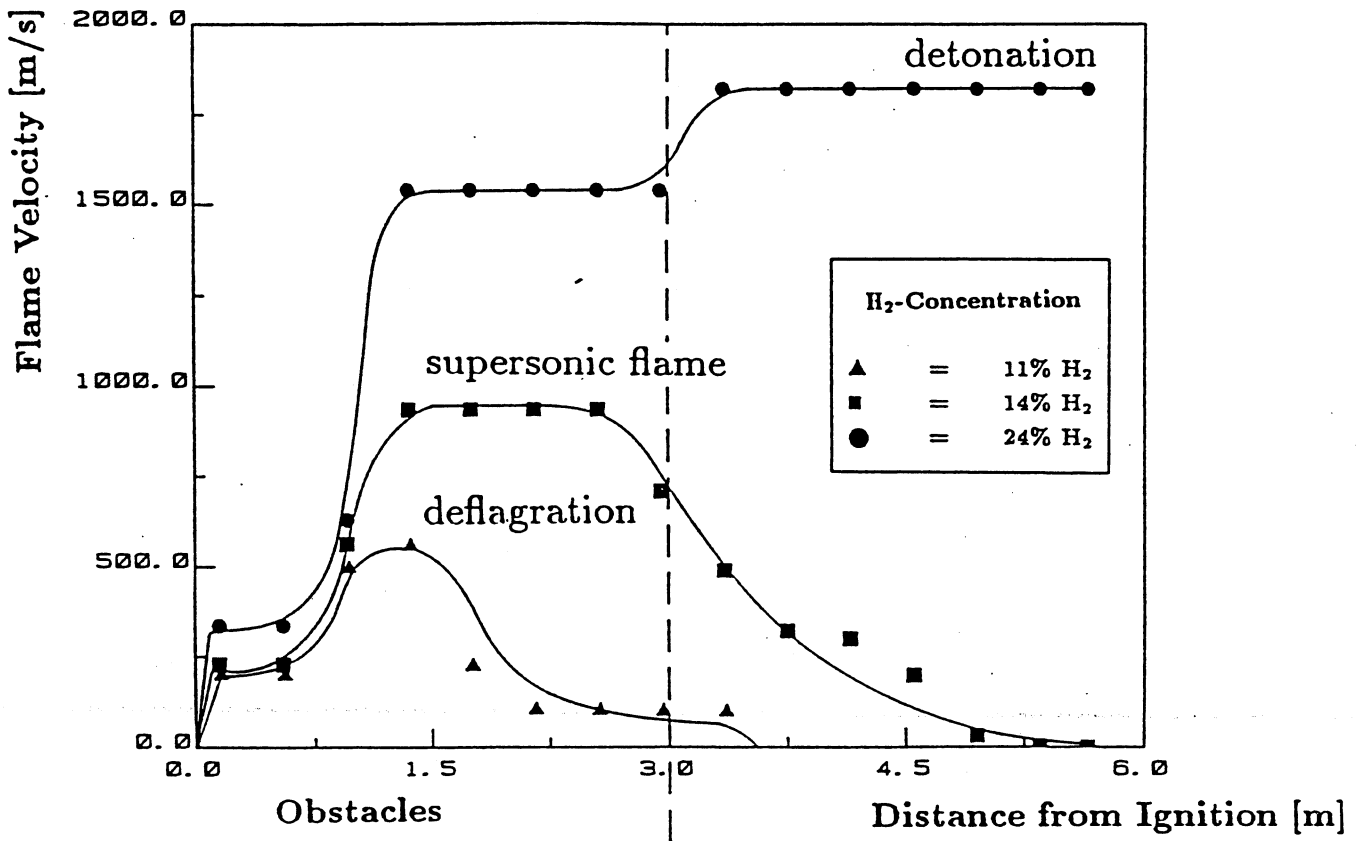


Fig. 5. Distribution of the flame front velocities of a premixed hydrogen/air flame along the axis of an explosion tube partly provided with turbulence promoting obstacles. The equivalent ratio of the mixture was varied between 11 vol.-% and 24 vol.-% (stoichiometry: 29,6 vol.-%) The three different combustion modes — deflagration, supersonic flame and detonation — can be clearly distinguished (Haibel (1991))

2.5.2. Diffusion flames: In many technical furnaces and propulsion systems the fuel is injected into an atmosphere containing the oxydizer. This means that in the course of the fuel jet penetration a combustible fuel/oxydizer mixture is generated in the jet boundary layer by means of diffusive mass transfer and large scale turbulent mass and momentum transfer between the fuel jet and the surrounding atmosphere. When igniting the combustible boundary layer a flame will occur which envelopes the penetrating fuel jet and separates it from the surrounding atmosphere. This type of flame is called diffusion flame as it is mainly controlled by mass diffusion processes between the fuel jet and the oxydizer atmosphere. A typical example of a furnace with diffusive combustion is a Bunsen burner (fig. 6). Diffusion flames are the most important types of flames in propulsion systems and will be therefore described in detail in the upcoming chapter 3 of this paper.

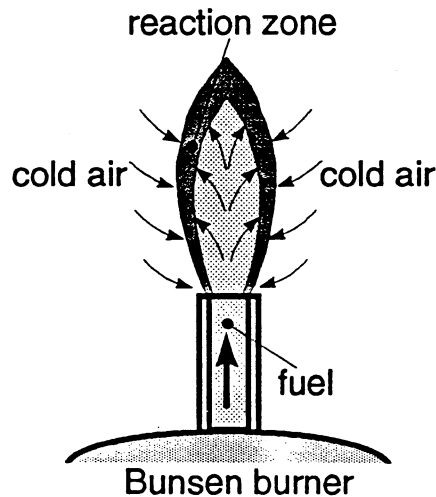


Fig. 6. Flow structure around the diffusion flame of a Bunsen burner fired with gaseous fuel

3. Diffusion flames in combustion chambers

3.1. MODEL OF DIFFUSION FLAMES

Diffusion flames are types of flames where fuel and oxydizer are not premixed as they enter the combustion chamber separately. This means that before the combustion process can start a combustible mixture has to be generated by means of mass diffusion and turbulent convective mass transfer. Three different zones can be classified in diffusion flames: injection zone (zone I), mixing zone (zone II) and combustion zone (zone III) (fig. 7).

In zone I the pure fuel jet is injected into the surrounding air flow. The design of the injection geometry is depending on the type of fuel, liquid or gaseous, and on the type of combustion chamber. In zone II of the diffusion flame the fuel jet penetrates into the surrounding air flow and fuel and air are mixed by means of diffusive and convective mass transfer. When using liquid types of fuel the fuel jet has to be atomized before the mixing process starts. In zone III the combustible mixture is preheated up to ignition temperature by means of mass diffusion, thermal conductivity and convective heat and mass transfer. Thereby clusters of hot burned reaction products are mixed with clusters of the cold unburned fuel/air mixture. Finally the so prepared fuel/air mixture reacts. Please note that the reaction process always takes place in the boundary layer separating the fuel jet and the surrounding air flow as only there a combustible fuel/air mixture will occur.

3.2. FUEL INJECTION AND MIXING PROCESS

Combustion processes in general are controlled by two different time scales, the thermofluidmechanical time scale and the chemical time scale. The thermofluidmechanical time scale is defined as the time it takes

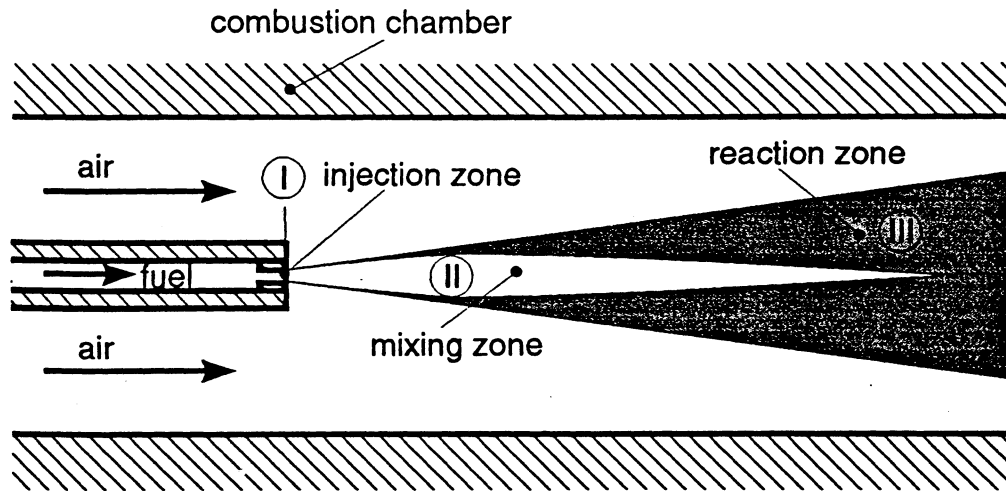


Fig. 7. Scheme of a airbreathing combustion chamber with parallel fuel injection and the three different zones of a diffusion flame: injection zone (I), mixing zone (II) and combustion zone (III)

to mix fuel and oxydizer and to preheat the combustible mixture up to ignition temperature by means of heat and mass transfer. The chemical time scale defines the reaction time for the complete oxydization of the fuel. In diffusion types of flames the thermofluidmechnical time scale is 5 to 6 orders of magnitude greater than the chemical reaction time. This leads to the general model of diffusion flames that predicts, that the overall behaviour of the flame and especially the flame length is completely controlled by heat and mass transfer processes and is thereby only depending on the structure of the mixing jet. Taking this into account, the injection and mixing process of the fuel is one of the most important factors for the design of combustion chambers.

Before demonstrating typical examples of fuel injectors, some fundamental requirements for injection systems and mixing process must be pointed out. First of all the injector must be adapted to the type of fuel. For gaseous fuels like hydrogen or methane a simple opening can be used for injection whereas for liquid fuels like kerosine or ethanol special designed nozzles are required to spread up the fuel jet, form a spray and atomize the fuel (Kuo (1986), Someya (1993), Mayinger (1992/1), Strehlow (1984)). In this case atomization means to generate very small droplets of fuel, so that the fuel can easily be evaporated (fig. 8).

Apart from the type of injection nozzle the controllability of the injection process concerning the variation of the fuel mass flow is of high importance. Especially for flight propulsion systems during the different flight regimes like take-off, cruise and landing the reliable and accurate injection of fuel must be ensured.

After passing the injection system the fuel jet has to penetrate deep into the surrounding air flow to force the mixing process. But a high penetration depth normal to the air flow may lead to an increase of the pressure drop in the combustion chamber due to the partly blockage of the air flow. So in the end there must be a compromise between an as great as possible penetration depth coupled with an as small as possible pressure drop.

The basic aim of a well designed fuel injector is to ensure an as short as possible mixing jet. By inducing large scale turbulent structures the convective mass transfer between the fuel jet and the air flow will be enhanced. This can be effected by inducing a swirl flow to the fuel jet or to the air flow or to both. Another possibility is to generate rezirculation zones downstream of the fuel injector by means of wedges, rearward facing steps or blunt bodies. A more simple but effective method to influence the

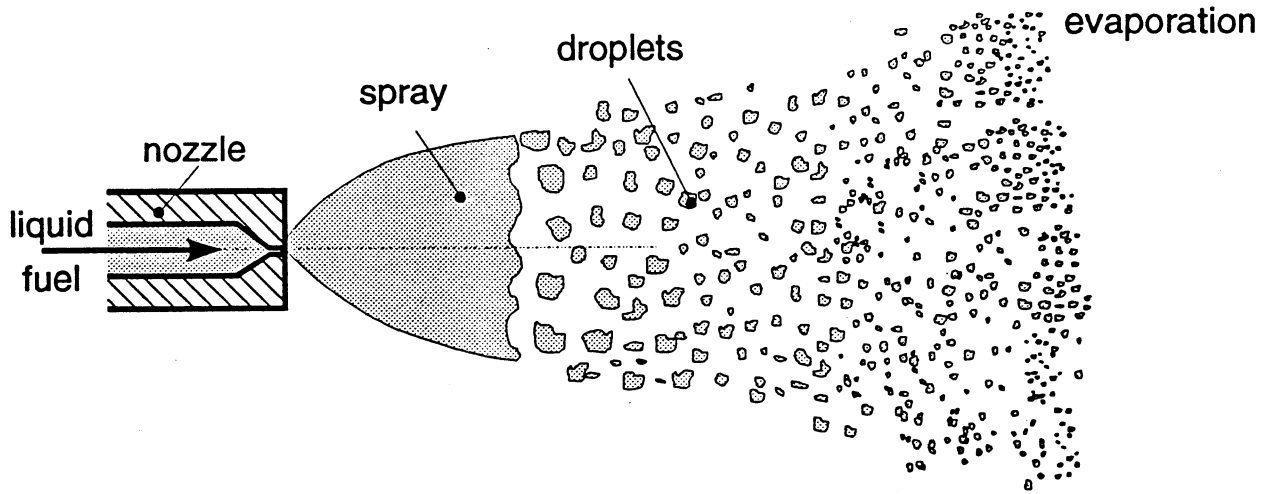


Fig. 8. Model of spray formation and fuel atomization in combustion chambers fired with liquid fuels

mixing process is to vary the injection angle of the fuel jet. At the Institute A for Thermodynamics at the University of Technology in Munich investigations on the mixing process of hydrogen and air in sub- and supersonic combustors were carried out. Therefore a two-dimensional combustion chamber was used, where the hydrogen was injected into the main air flow under different injection angles with different injection geometries like single hole injection, twin hole injection and slot injection (fig. 9).

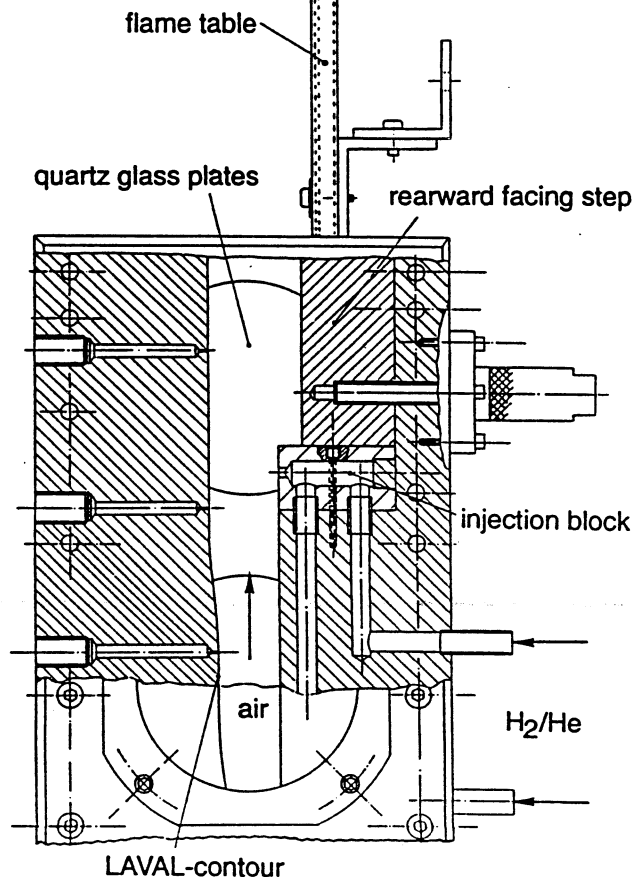


Fig. 9. Sketch of the combustion chamber for the investigation of the behaviour sub- and supersonic hydrogen/air diffusion flames

Downstream of the injection block, figure 9 shows a rearward facing step which was inducing a rezirculation zone. By varying the height of the rearward facing step and thereby varying the large scale turbulent structure of the hydrogen/air mixing jet, it could be seen, that the mixing efficiency was enhanced very much by increasing the degree of turbulence (Mayinger (1992/2), Haibel (1992)).

Figure 10 shows the concentration profiles of the mixing jet when varying the injection angle. The air Mach number was 0.6 and the profiles were determined by means of holographic interferometry. It can be seen that with increasing injection angle (parallel to normal) the mixing length decreases significantly.

Apart from the single hole, twin hole and slot injectors a number of other types of injection systems are regarded like multi hole injectors, arrowshaped ramps and microstruts. The basic principle of all these types of injection systems is to promote the mixing process by inducing macroscopic turbulent structures. Figure 11 shows a selection of different injection systems for gaseous fuels in airbreathing engines. Additional information on the injection and mixing process is given by Rogers (1972), Rick (1974), King (1989), Cohen (1970), Suttrop (1971), Northam (1989), Parr (1993), Haibel (1992) and Northam (1991).

3.3. FLAME STABILIZATION

Flame stabilization is one of the most important operation factors for combustion chambers concerning the safety and reliability of propulsion systems. So flame extinction has to be avoided under any operation condition of the combustion chamber as re-ignition of the flame is often very difficult and dangerous or even impossible.

Flame stabilization means that the local burning velocity u_B is equal and antiparallel to the local flow velocity u_F .

$$\overline{u_B} = -\overline{u_F}$$

As discussed in chapter 2 of this paper, the burning velocity u_B is a function of the equivalent ratio γ of fuel and air, the pressure p , the temperature T and the degree of turbulence Tu ,

$$u_B = f(p, T, \gamma, Tu)$$

and can be controlled by varying these parameters. When inducing a high degree of turbulence in a near stoichiometric hydrogen/air mixture the burning velocity can be increased up to 50 m/s. In general it can be said, that high degrees of turbulence appear in turbulent free shear layers in the wake of blunt bodies or rearward facing steps. These shear layers separate the main flow field and the rezirculation zone behind those bodies, which are normally called flame holders. Figure 12 shows the flow field in the vicinity of the rearward facing step, which occurs in the sub- and supersonic combustion chamber described earlier in this chapter.

On the one side the degree of turbulence Tu is very high inside the turbulent free shear layer, so that the burning velocity will be promoted very much. On the other side there are fairly low flow velocities u_F in the shear layer, so that there will be a burning velocity which is equal to the flow velocity. And this is the exact condition for stabilizing flames. In other words, inside the turbulent free shear layer, which is depending on the Reynolds number of the initial flow, are always the required thermofluidmechanical conditions to stabilize a diffusion flame, even in high flow velocities (Haibel (1993)).

As the structure of the free shear layer changes with changing Reynolds numbers of the initial flow field, the stabilization area of the flame will move up- and downwards inside the shear layer when changing the initial air flow velocity. Figure 13 shows hydrogen/air flames at different air Mach numbers and hydrogen mass flow rates stabilized in the free shear layer in the vicinity of a rearward facing step. It can be seen, that the stabilization area of the flames move downwards with increasing initial air flow velocities and moves upwards with increasing hydrogen mass flow rates.

If the turbulent free shear layer is fully developed, the above described stabilization of the flames is a self controlling mechanism. But under certain circumstances, e.g. low air flow velocities or very high hydrogen mass flow rates, the shear layer may not be fully developed. This leads to unstationary

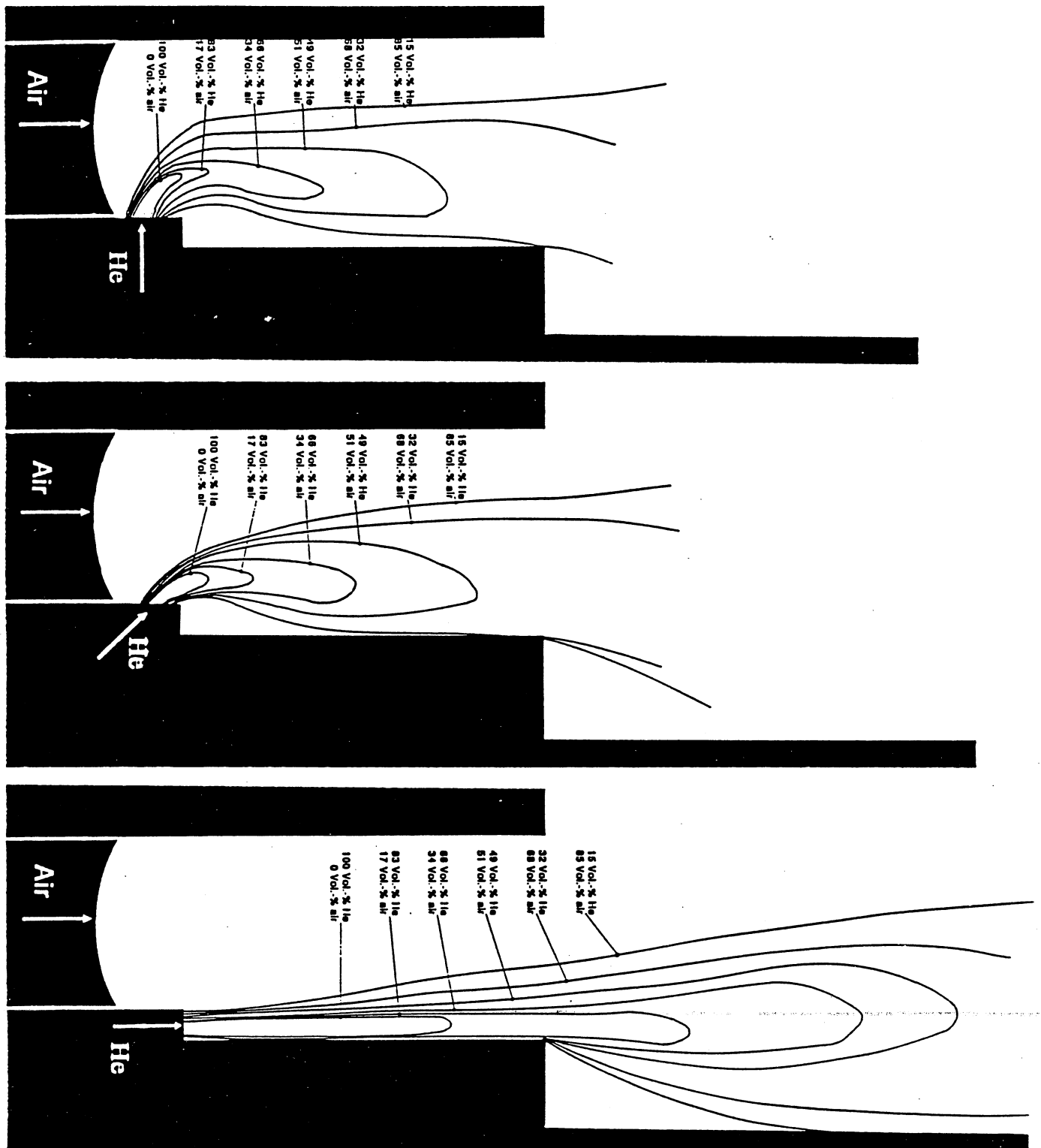


Fig. 10. Influence of the injection angle on the concentration profiles of the mixing jet with an air Mach number of 0.6 determined by means of holographic interferometry. As the investigations were done without combustion, helium was used instead of hydrogen. (Haibel (1992), Haibel (1993), Mayinger (1992/2))

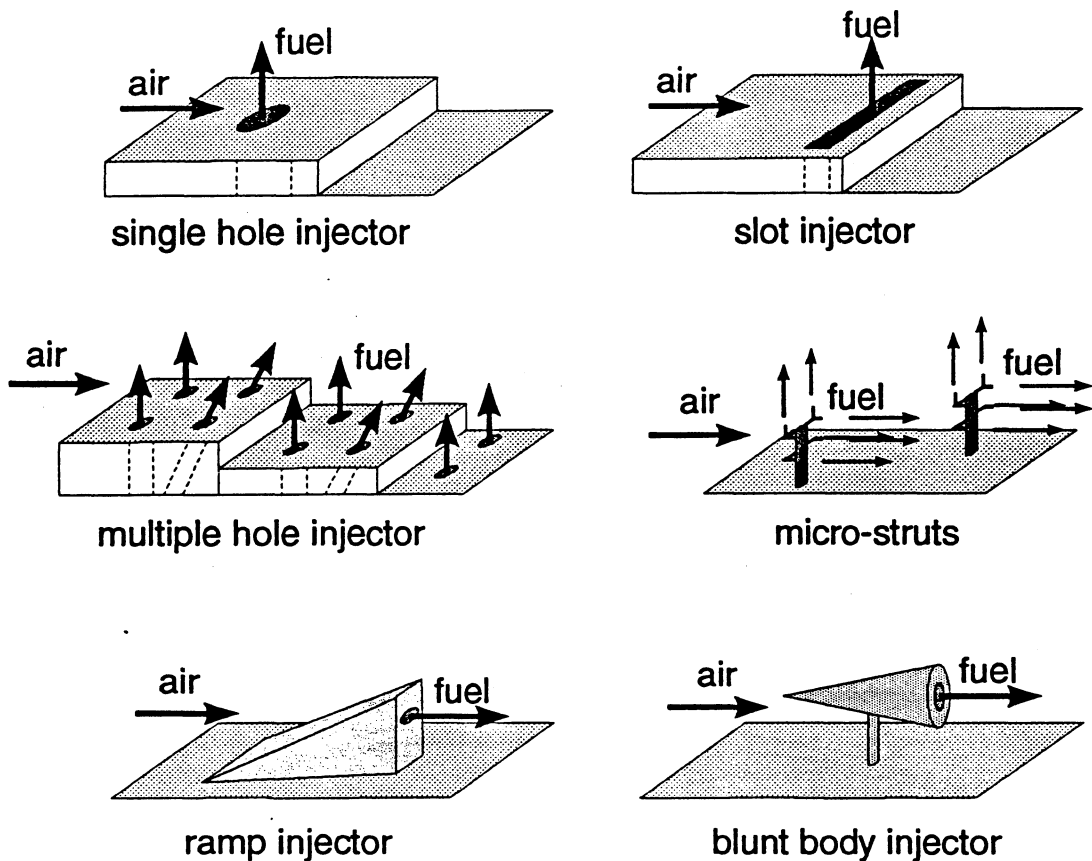


Fig. 11. Selection of injection systems utilized for gaseous fuels in airbreathing engines

fluctuations of the flow properties in the shear layer which effect the stabilization conditions of the flames. Figure 13 shows the temporal behaviour of a hydrogen/air flame stabilized at the lower stabilization limit in an undeveloped free shear layer. It can be seen, that the stabilization area moves up- and downstream and that the distribution of the reaction zones is completely irregular compared to the flames shown in figure 12.

Finally it can be said, that each type of flame holder — rearward facing step, blunt body or free recirculation zone induced by swirl flow — face the same physical principle, inducing a turbulent free shear layer with a high degree of turbulence coupled with a low flow velocity to adapt the burning velocity to the flow velocity (Wilhelmi (1973), Günther (1984)).

3.4. FLAME STRUCTURE

For the design of combustion chambers it is important to have some information on the structure and behaviour of the overall flames. First of all, as mentioned before, the structure of the flame is very much linked to the structure of the mixing jet. But there are some effects connected to the burning process which may influence the behaviour of the flame. As long as the flame burns in the subsonic regime, pressure waves induced by inhomogenous combustion travel in the upstream direction of the flame. It was mentioned before, that the burning velocity is influenced by the initial pressure of the combustible mixture, so that those pressure waves will change the local burning velocity. This change in the burning velocity again will build up new pressure waves. This circle of flame oscillations may lead to an amplification or an extenuation of the pressure waves, depending on the acoustic signature of the combustion chamber. The amplification of the pressure waves may lead to a destruction of the combustion chamber due to resonance effects. One possible measure to prevent flame oscillations is to inject the fuel in a well

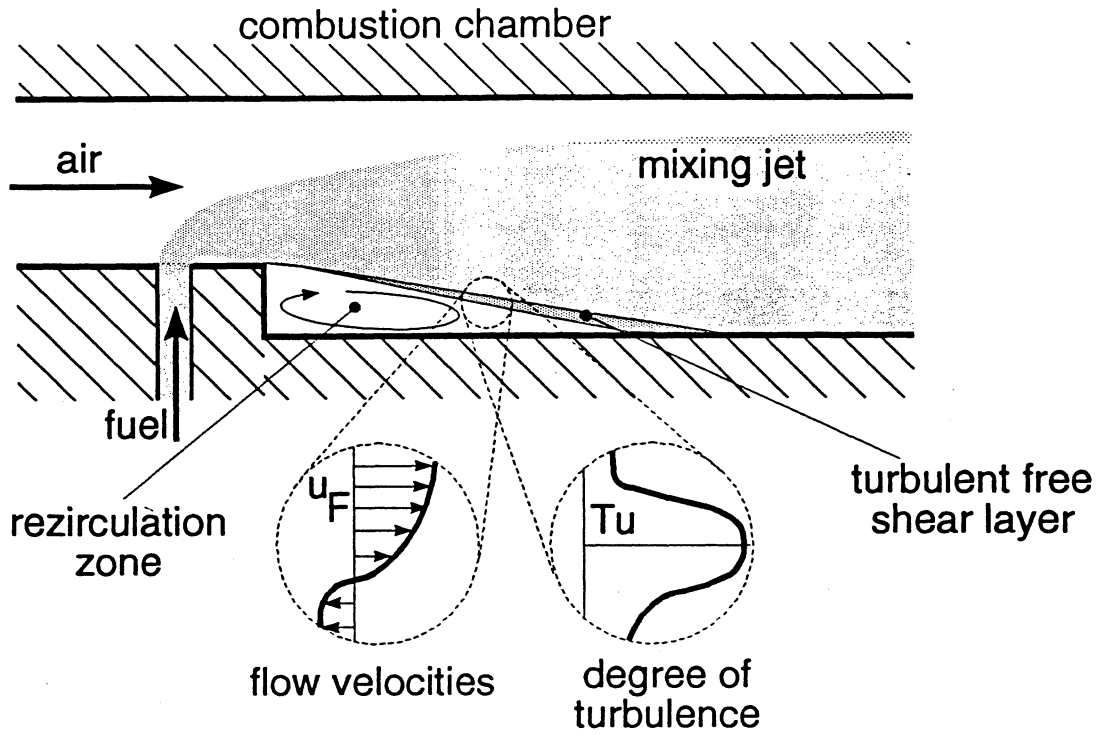


Fig. 12. Flow field in the vicinity of a rearward facing step with upstream hydrogen injection

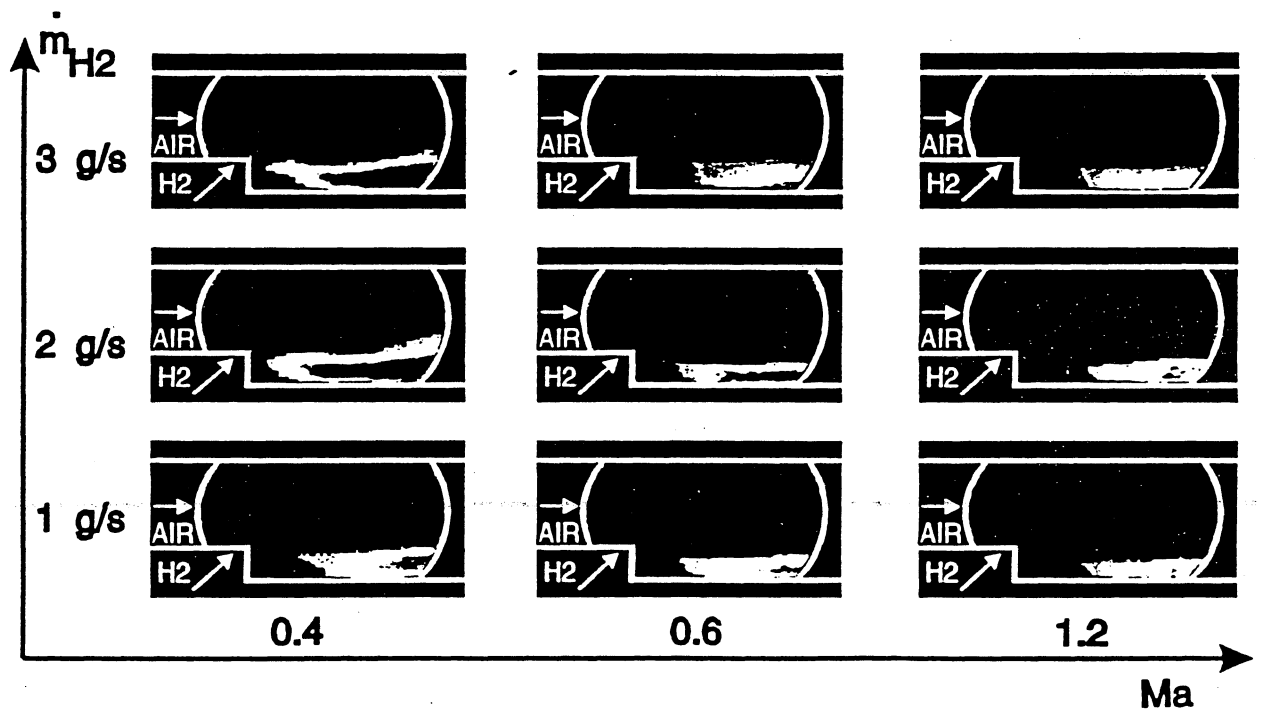


Fig. 13. Influence of the initial air Mach number and the hydrogen mass flow rate on the stabilization of a hydrogen/air flame in the vicinity of a rearward facing step recorded by means of self fluorescence (originally in false colors) (Haibel (1993))

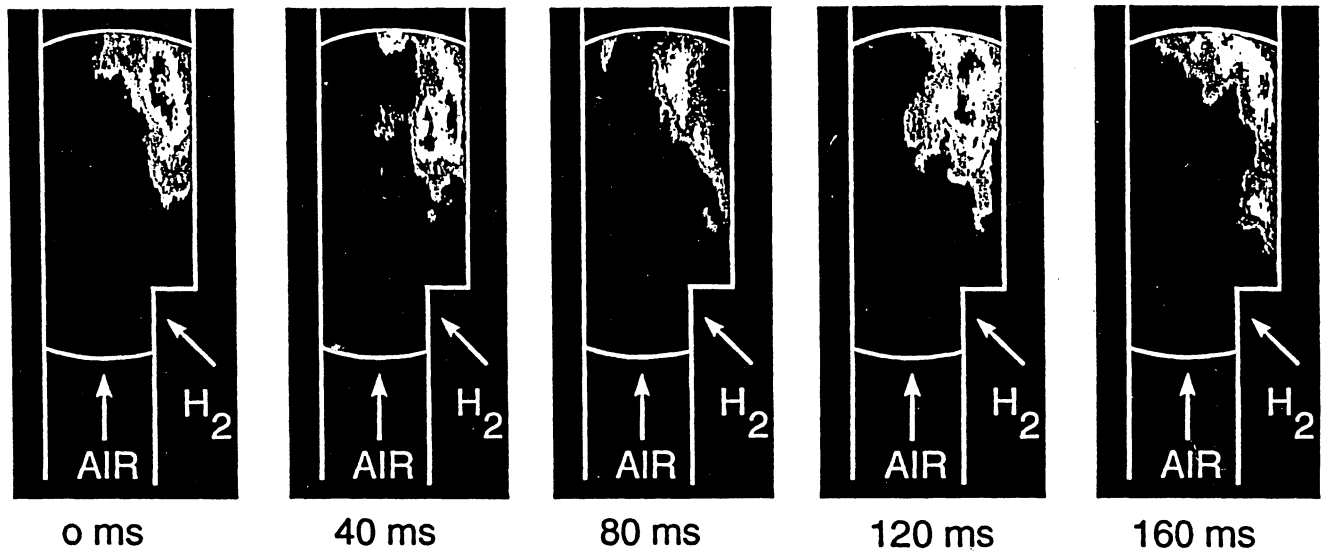


Fig. 14. Temporal behaviour of a Mach 0.2 hydrogen/air flame stabilized in an undeveloped free shear layer recorded by means of self fluorescence (originally in false colors). The temporal distance between two images is 40 ms. (Haibel (1993))

controlled pulsating jet with a pulse frequency far away from the resonance frequencies of the combustion chamber (Someya (1993)).

When looking at the reaction front distribution of a diffusion flame, it can be recognized that large scale turbulence do not only effect the mixing process in front of the flame, but also the rate of reaction within the shape of the flame. Figure 15 shows the top view of hydrogen/air flames at two different air Mach number (0.6 and 1.2) recorded downstream of the exit cross section of the combustion chamber described earlier.

It can be seen that in the Mach 0.6 flame a pair of stable vortices enhance the mixing rate in the flame which leads to an increase of the reaction rate. When increasing the air flow velocity ($Ma=1,2$) the pair of vortices are elongated and unite in the center of the flame. This causes an overall increase of the mixing and thereby reaction rate in the flame and leads to a decrease of the flame length.

In general it can be said that the structure and behaviour of flames is very much influenced and thereby controllable by large scale turbulent structures and the structure of the fuel/air mixing jet.

4. Conclusion

It could be shown that the structure and behaviour of sub- and supersonic flames can be explained by using the fundamental principles of chemical reactions, heat and mass transfer and turbulent flow described in chapter 1 and 2 of this paper. Diffusion types of flames as they occur in propulsion systems for aeronautical and space application are very much controlled by the fuel/air mixing jet. Apart from the geometry of the fuel injector the mixing process can be influenced by inducing large scale turbulent structures. Experiments in high speed hydrogen/air flames proved that supersonic combustion chambers can not only be run without preheating of the incoming air, but the flames can be stabilized within

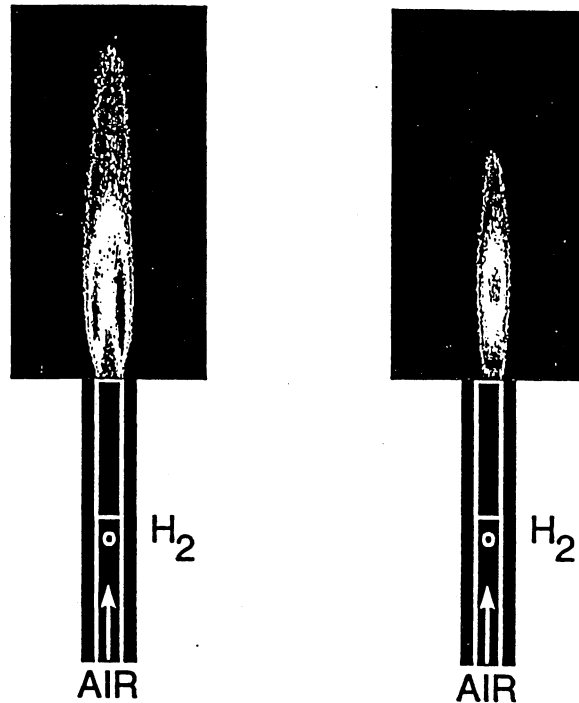


Fig. 15. Reaction zone distribution of two hydrogen/air flames at different air Mach numbers (left: $Ma=0.6$; right: $Ma=1.2$) recorded downstream of the exit cross section of the combustion chamber by means of self fluorescence (originally in false colors). (Haibel (1993))

a wide range of air flow velocities simply by inducing high degrees of turbulence to the mixing jet. Finally it could be shown that the overall structure and behaviour of sub- and supersonic flames can be controlled by large scale turbulent structures influenced by the combustion chamber geometry. More detailed information on the design of special types of combustion chambers will be provided in the papers 21, 22, 23, 24, 27, 28, 30, 31 and 32 of this space course.

Nomenclature

A	area of flame front in $[m^2]$
A_T	area of turbulent flame front in $[m^2]$
$A_{min,m}$	minimum molare demand of air in $[kmol / kmol \text{ fuel}]$
a_{min}	minimum demand of air in $[kg / kg \text{ fuel}]$
$c_{p,m}$	molare heat capacity at constant pressure in $[kJ / kmol K]$
ΔH_m	molare heat of reaction in $[kJ / kmol]$
m	mass fraction in $[kg / kg \text{ fuel}]$
n	number of moles in $[kmol]$
p	pressure in $[Pa]$
$O_{min,m}$	minimum molare demand of oxygen in $[kmol / kmol \text{ fuel}]$
o_{min}	minimum demand of oxygen in $[kg / kg \text{ fuel}]$
s_L	laminar burning velocity in $[m/s]$
T	temperature in $[K]$
t	temperature in $[^\circ C]$
Tu	degree of turbulence in $[-]$
u	flow velocity in $[m/s]$
γ	molare fraction in $[-]$

λ equivalent ratio of oxygen and fuel in [-]

subscripts

B	property of the burning flame front
eg	exhaust gas
F	fuel
m	molare
max	maximum
min	minimum
1	property in front of the flame front

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