EXPERIMENTAL INVESTIGATION OF THE MIXING PROCESS AND THE FLAME STABILIZATION IN SUB- AND SUPERSONIC HYDROGEN/AIR FLAMES

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ABSTRACT

The development and structure of the mixing and combustion process in sub– and supersonic hydrogen/air flames was investigated by means of optical measurement techniques. The experiments showed, that the development of the mixing jet was very much controlled by the impact of macroscopic turbulence and could be described with analytical formulae. The use of a rearward facing step enabled the stabilization of the flame under all operation conditions of the combustion chamber up to supersonic speed. The structure and stabilization of high speed hydrogen/air flames could be explained by the enhancement of the burning rate due to turbulent flame front acceleration.

1. INTRODUCTION

In the framework of international research activities, the application of hydrogen as an energy carrier in propulsion systems as a substitute for fossile fuels is investigated. Thereby three major aspects of stationary hydrogen diffusion flames must be understood more deeply: the mixing process of hydrogen and air, the mechanism of flame stabilization, and the overall flame structure depending on the flow conditions in the combustion chamber.

A number of theoretical and experimental works were published in the past, dealing with the injection, mixing and burning of gaseous types of fuels in high speed air flows, focussing supersonic and hypersonic airbreathing propulsion systems (Billig (1993), Fuller et al (1992), Bakos et al (1992), Schetz et al (1991), Takahashi et al (1991), Bussing et al (1990), Schetz (1980)). The purpose of these papers was to describe the mixing and combustion process due to the mixing jet penetration, the shock/jet interactions, the development of the concentration profile in the mixing jet, and the temperature distribution in the stabilized flame.

The object of this paper is to demonstrate the effect of turbulence on the development of the mixing jet and on the stabilization of high speed hydrogen/air flames in a wide range of inlet air Mach number up to supersonic speed, using a rearward facing step as a turbulence promotor. The mixing and combustion processes were visualized using non–intrusive diagnostic methods like holographic interferometry and OH self fluorescence.

2. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

The experimental investigations concerning the mixing and combustion processes of high speed hydrogen/air flames were performed in a combustion chamber sketched in Figure 1. Pressurized air with a stagnation temperature of T_0=291K was accelerated in an asymmetric 2–dimensional LAVAL–nozzle. Thereby the inlet air flow velocity could be varied between 25 m/s (Ma_∞=0.07) and 445 m/s (Ma_∞=1.3). A rearward facing step downstream of the fuel injection block was used to induce turbulent flow structures and to generate a turbulent recirculation zone for promoting the mixing process and the stabilization of the flame. The side walls of the combustion chamber were equipped with quartz glass windows to acquire transperancy for optical measurement techniques in the visible and the ultraviolet spectrum. A more detailed description of the experimental setup is given in Haibel (1994).

The experiments were subdivided into two parts. The first part was the investigation of the mixing process in the near field of the injector. These experiments were done without combustion ('cold mixing') using helium as a substitute for hydrogen. The second part dealed with the investigation of the combustion process concerning the stabilization and the behaviour of the hydrogen/air flames.

The mixing processes of helium and air were investigated by means of holographic interferometry using the

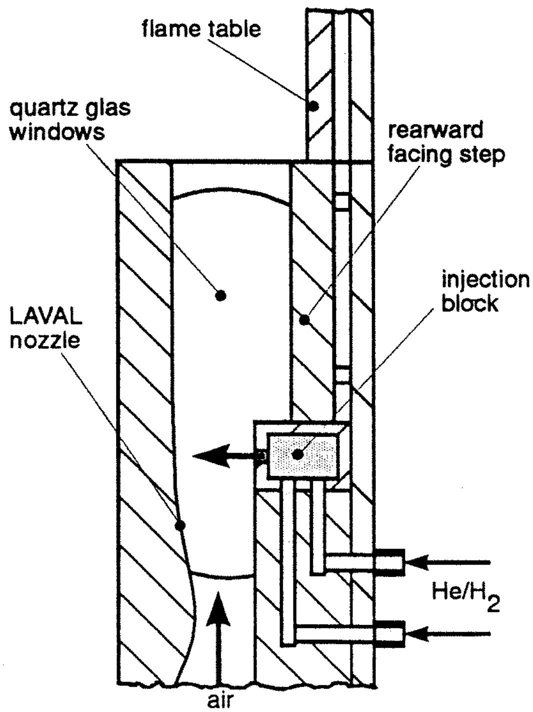

Fig. 1: Sketch of the combustion chamber

'finite fringe' method (Hauf (1970) Mayinger (1994). The thereby received interferogramms were analyzed with respect to the spatial growth, the penetration and the concentration profiles of the mixing jets. The combustion processes were investigated by means of OH self fluorescence (Haibel et al (1993)). This technique, which is based on the effect of chemoluminescence, was used to visualize the spatial and temporal distribution of the reactions zones, and to determine the flame length and the location of the flame ignition spot .

3. DEVELOPMENT AND BEHAVIOUR OF THE HELIUM/AIR MIXING JET

Figure 2 shows a series of interferograms demonstrating the dependency of the mixing jet on the inlet air Mach number Ma_∞. The injection of the helium was realized with a single hole injector perpendicular to the air flow direction. The specific mass flow rate of helium $(\rho u)_{He}$ was 116.2 kg/m^{2}s.

It can be seen, that with an inlet air Mach number of $Ma_\infty=0.19$ the mixing jet penetrates deep into the surrounding air flow field and is quickly deflected towards the air flow direction. It can be seen, that the outer boarder of the mixing jet is very rugged, which indicates the impact of macroscopic vortices on the free mixing shear layer. An increase of the air Mach number leads to a decrease of the penetration and to a stronger deflection of the mixing jet, as the specific momentum ratio of helium and air decreases. Nevertheless, the outer boarder of the jet stays very rugged. When reaching supersonic air Mach numbers ($Ma_\infty=1.12$), the mixing jet becomes very slender and falls together with the free shear layer in the wake of the rearward facing step.

Figure 3 shows the holographic interferogram of a Mach 0.43 mixing jet and the corresponding concentration profile. It can be seen, that in the vicinity of the injector, the gradient of the concentration is very high and decreases when moving downstream. Within the first few centimeters downstream of the injector, the mixing process is very much enhanced by vortices generated in the wake of the mixing jet and in the recirculation zone of the rearward facing step. This leads to a strong decrease of the concentration in the center of the jet. Furthermore it can be seen, that the trajectory, which represents the line of maximum local concentrations in the mixing jet, is also deflected quickly into the main air flow direction, and then moves towards the bottom of the rearward facing step. During the development of the mixing jet, the recirculation zone in the wake of the rearward facing step is filled with a near stoichiometric helium/air mixture. This fact is very important for the flame stabilization described later in this paper.

The investigations led to an empirical Eq. (1), which describes the growth of the outer boarder and the penetration of the mixing jet, raised from the received interferogramms. Thereby a rectangular coordinate system is used, which is located in the center of the injector nozzle with the coordinate x in the direction of the main air flow and the coordinate y perpendicular to it describing the jet penetration. The equation, which is normalized with the injection nozzle diameter d_0, has the same growth coefficient of 0.087 as given by Orth et al (1967).

$$\frac{y}{d_0} = 1.6 \cdot \xi_{He}^{0.65} \cdot Ma_\infty^{-1.15} \cdot \left(\frac{x}{d_0} + 0.01\right)^{0.087} \qquad (1)$$

In Eq. (1) ξ_{He} is the ratio of the specific mass flow rate of the injected helium $(\rho u)_{He}$ and the critical specific mass flow rate of helium $(\rho u)_{He,crit}$ ($\xi_{He} = (\rho u/\rho u_{crit})_{He}$). The critical specific mass flow rate is defined as the maximum mass flow rate which araises, when the Mach number of the injected helium in the exit cross section of the injector nozzle is equal to

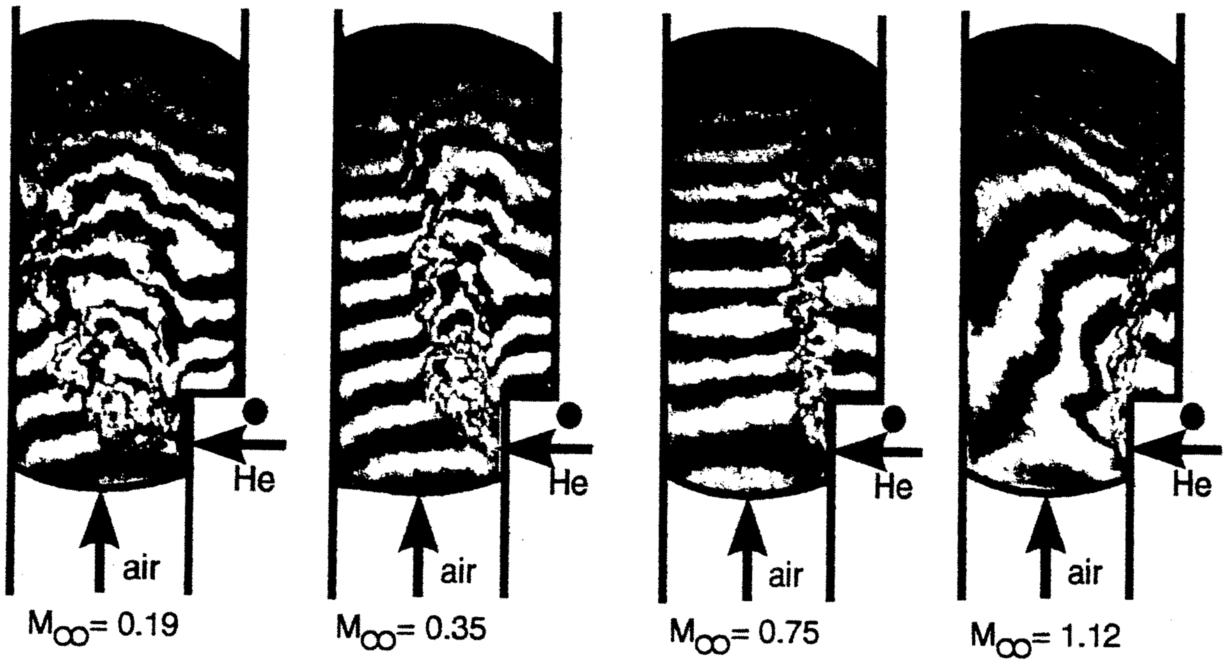

Fig. 2: Holographic interferograms showing the development of the mixing jet depending on the inlet air Mach number Ma_∞ (ξ=0.63)

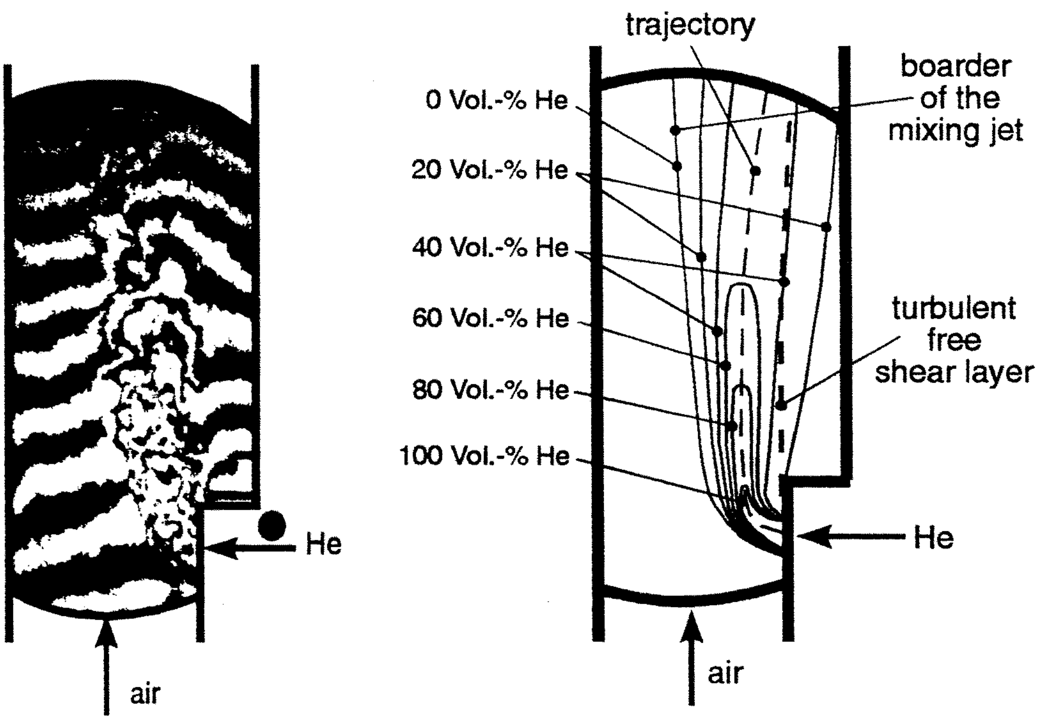

Fig. 3: Holographic interferogram and the corresponding concentration profile of a Mach 0.43 helium/air mixing jet (ξ_{He}=1.14)

unity. Knowing the static pressure p_{exit} at the exit cross section of the injector nozzle, the critical specific mass flow rate can be calculated using Eq. (2):

$$(\rho w)_{He;crit.} = \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \cdot \sqrt{\frac{\gamma}{\gamma+1}} \cdot p_{exit} \cdot \cdot \left(\frac{2}{\gamma+1}\right)^{-\frac{\gamma}{\gamma-1}} \cdot \sqrt{\frac{2}{R_{i,He} \cdot T_{0;He}}} \quad (2)$$

Eq. (1) shows, that the mixing jet becomes slender and the penetration decreases with increasing air Mach number, and becomes broader with an increasing ratio of the helium mass flow rate ξ_{He}.

The concentration profile c(x', y') in [Vol.-% He], which araises between the inner and outer boarder of the mixing jet, can be calculated with good accuracy using Eq. (3). Thereby a rectangular coordinate system (x', y') is used, which originates from the trajectory, so that x' and y' are parallel to x and y, but with y'=0 representing the maximum local concentration for any value of x'.

$$c = c_{max} \cdot exp\left(-K \cdot \left(\mid \frac{y'}{x'} \mid\right)^3\right) \quad (3)$$

c_{max}, which represents the maximum local concentration on the trajectory of the mixing jet, is given by

$$c_{max} = 100 \cdot exp\left(0.0653 \cdot \left[log(4 \cdot Ma_{\infty}^{0.28})\right]^{-1} \cdot \cdot \left(\frac{x'-x'_p}{d_0}\right)^{0.7}\right) \quad (4)$$

with x'_p representing the beginning of the fully developed flow region of the mixing jet. x'_p is depending on the inlet air Mach number and on the injected mass flow ratio, and can be determined by:

$$\frac{x'_p}{d_0} = 13.9 \cdot \xi_{He}^{0.58} \cdot log\left[10 \cdot Ma_{\infty}^{0.85}\right] \quad (5)$$

The constant K in Eq. (3), which is controlled by the gradient of the concentration profile, is a function of the inlet air Mach number can be calculated by:

$$K = 1425 \cdot \xi_{He}^{0.89} \cdot log\left[10 \cdot Ma_{\infty}^{2.06 \cdot \xi_{He}^{0.93}}\right] \quad (6)$$

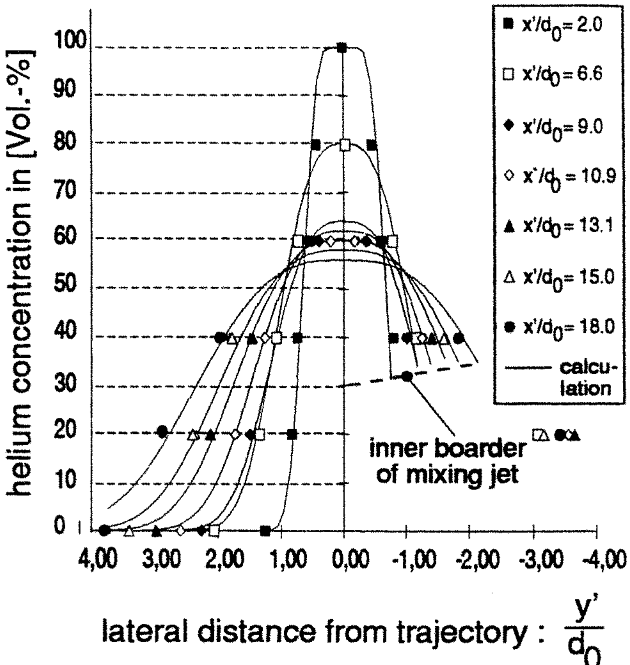

Fig. 4: Measured (symboles) and calculated (lines) concenteration profile of a helium/air mixing jet with Ma_{∞}=0.43 and ξ_{He}=1.14 (see Fig. 3)

Figure 4 shows a comparison of the determined concentration profiles shown in Figure 3 with the calculated profiles using Eqn. (3) – (6). It can be seen, that between the inner and outer boarder of the mixing jet, the calculations correspond very good with the measurements. It is important to note, that Eq. (3) is only valid for the fully developed flow region of the jet.

4. STABILIZATION OF HIGH SPEED HYDROGEN/AIR FLAMES

Figure 5 shows the image of a hydrogen/air flame at Mach 0.96, recorded by means of OH self fluorescence. It can be seen, that the greatest part of the burning process happens downstream of the combustion chamber, with the highest burning rate in the center of the flame. The figure shows, that the flame ignition spot is located downstream in the wake of the rearward facing step in the vicinity of a turbulent free shear layer.

Figure 6 shows the development of a turbulent free shear layer in the wake of the rearward facing step. The Figure indicates a very turbulent flow structure, caused by the velocity gradient between the main air flow field and the flow field of the recirculation zone in the wake of the rearward facing step. Comparing the free shear layer with the flame shown in Figure 5, it can be seen, that the flame ignition spot is located at the inner boarder of the shear layer. It can also be

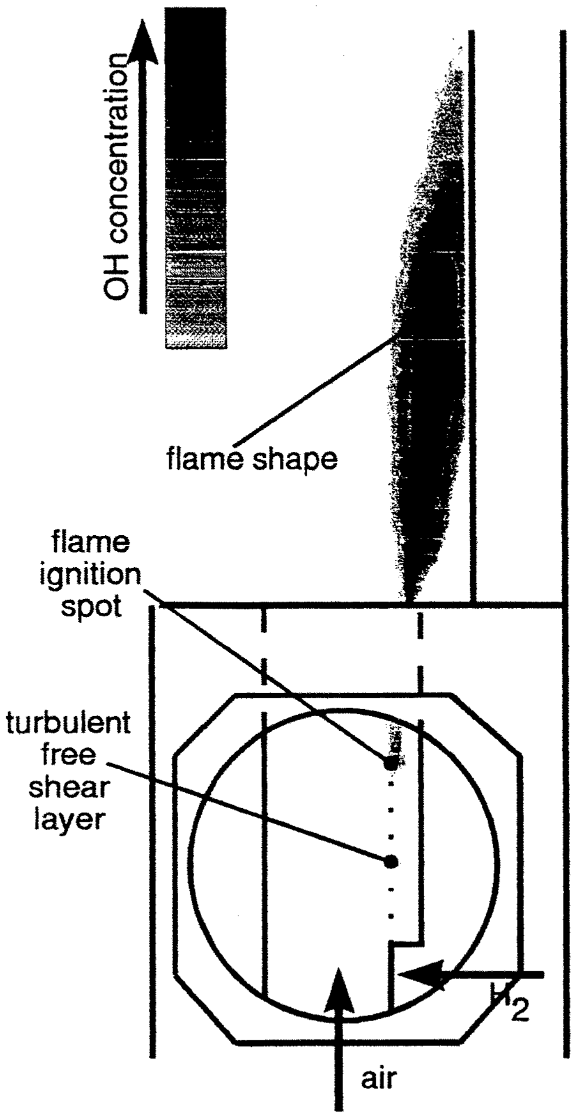

Fig. 5: Reaction zone distribution of a high speed hydrogen/air flame stabilized in the wake of a rearward facing step (Ma_∞=0.96; $(\rho u)_{H_2}$=54.9 kg/m^{2}s).

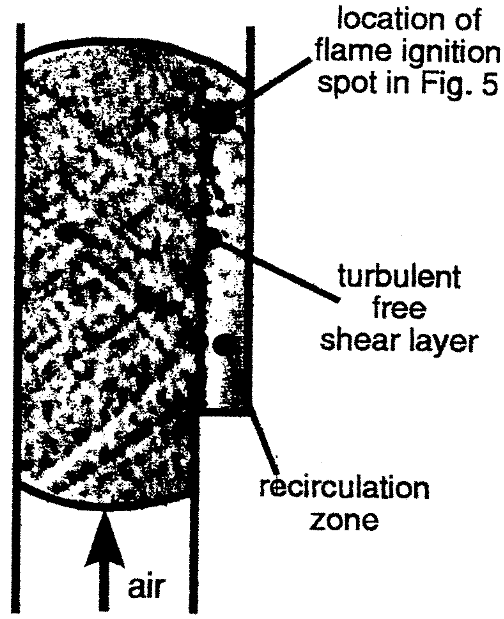

Fig. 6: Development of the free shear layer, generated in the wake of the attachment point of the rearward facing step (Ma_∞=0.96)

seen from Figure 3, that at the location of the flame ignition spot, the hydrogen concentration is about 40 Vol.-%. With this concentration, the burning velocity in a hydrogen/air flame is at its maximum. Together with the turbulent flow structure, which also increases the burning velocity, the inner boarder of the free shear layer provides the best burning conditions for the flame ignition spot.

Figure 7 shows the dependency of the flame ignition spot and of the flame shape on the inlet Mach number Ma_∞. It can be seen, that the flame ignition spot is slightly below the prolongation of the edge of the rearward facing step, which is identical with the inner boarder of the turbulent free shear layer. It can also be seen, that the flame ignition spot is moving downstream and that the flame becomes slender with increasing inlet Mach number.

5. CONCLUSIVE REMARKS

The experiments showed, that the turbulent vortex structure, which was induced in the vicinity of the mixing jet and of the free shear layer, was the leading controll parameter for the development and the behaviour of high speed hydrogen/air flames. The flames could be stabilized in the wake of the rearward facing step under all operation condition of the combustion chamber. It could also be seen, that the hot exhaust gases

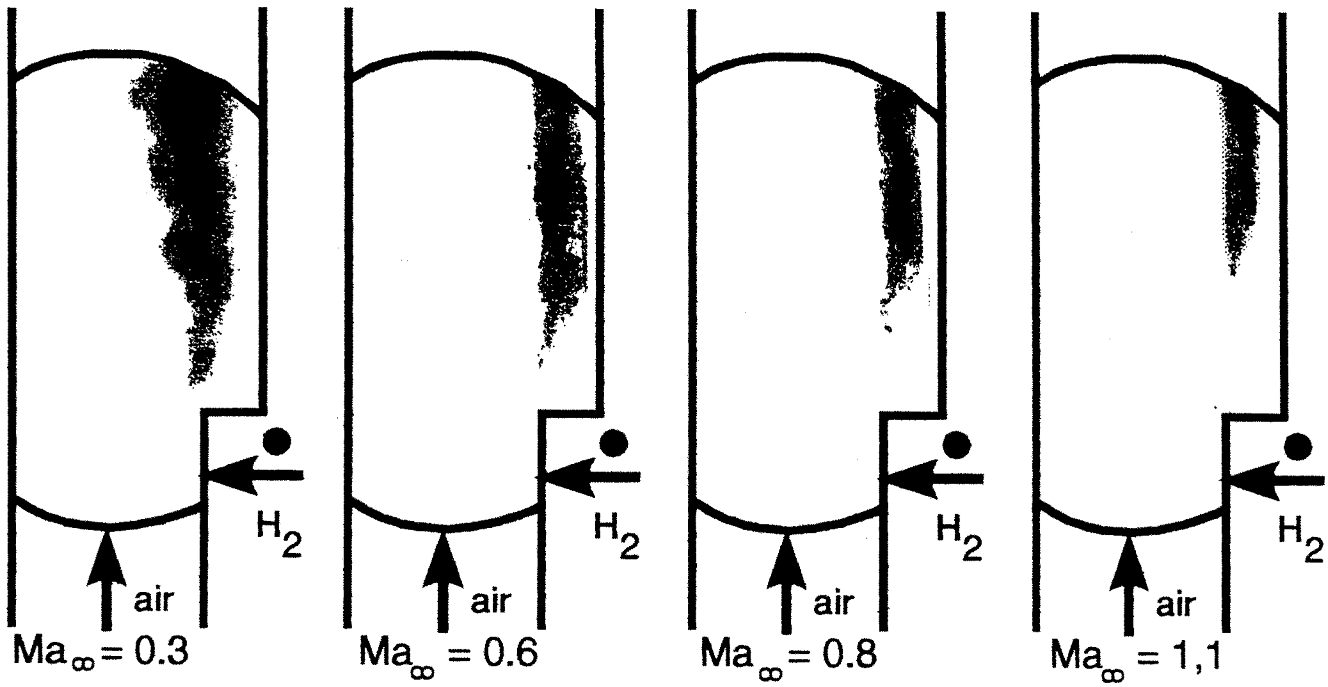

Fig. 7: Location of the flame ignition spot and shape of the hydrogen/air flame in the wake of the rearward facing step depending on the inlet Mach number Ma_∞ ($(\rho u)_{H_2}$=79.6 kg/m^{2}s)

in the recirculation zone helped to stabilize the flame in the free shear layer due to an additional increase of the burning velocity effected by the preheating of the combustable mixture.

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