MIXING PROCESS IN REACTING AND NON-REACTING SUPERSONIC FLOWS

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Abstract. The influence of shock patterns, rearward facing steps and multistep fuel injection on mixing and combustion processes in supersonic hydrogen/air flames was investigated by means of non-intrusive optical measurement techniques. The tests showed that rearward facing steps and multistep fuel injection generate vortices in the mixing jet which enhanced the mixing and combustion processes.

1. Introduction

A better fuel and air mixing would lead to higher combustion efficiencies and lower emissions of propulsion systems. The mixing process is influenced by shocks and expansion waves and turbulent structures in the flow field of the combustion chamber [1,19]. These structures are originated by the combustor geometry and the injected fuel jet.

The intention of this contribution is to provide detailed data about the effect of cascades of rearward facing steps on the mixing and combustion processes. Thereby the influence of flow characteristics like shock patterns and expansion waves on the fuel/air mixing are demonstrated. The influence of multistep fuel injection on the development of mixing and the turbulent structure of sub- and supersonic H_2 flames were also investigated.

2. Experimental Setup

The investigations on mixing and combustion processes in the supersonic flow field were performed in supersonic multistep combustor. The initial air Mach number of the main airflow was 2.1. The total temperature of the airstream was 293 K and the mass flow of the air was 850 g/s. The entrance cross section of the combustor was 25 x 25 mm. Three downstream rearward facing steps were used in the multistep combustor to generate large scale turbulent structures to receive fine-scale mixing and

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conditions of flame stability. Due to the height of the steps of 10 mm the exit cross section of the combustor was 25 x 55 mm. Upstream of the steps 1 and 2 fuel was injected through a line of injection holes mounted in steps 1-2. The mass flow of the injected fuel was varied from 0 to 10 g/s. All chamber walls were equipped with quartz glass windows to enable the access of optical measurement techniques (i.e. Raman Spectroscopy, laser induced fluorescence and shadowgraph technique [20-22]). Figure 1 shows a sketch of the multistep combustor.

To examine the mixing effects without the influence of chemical processes the fuel/air mixing was investigated in experiments without combustion ('cold mixing') using helium as model gas instead of hydrogen because of safety considerations. In experiments with combustion the turbulent flame structure and the flame stabilization were investigated by injecting hydrogen.

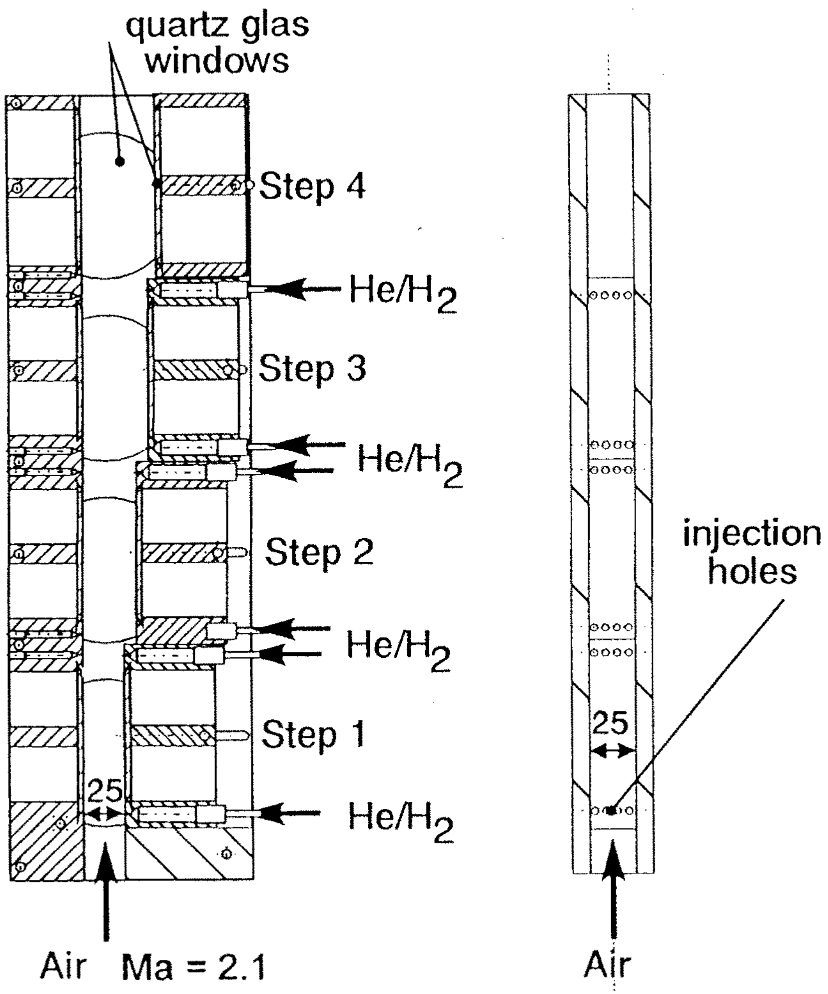

Fig. 1: Multistep combustor

3. Experimental Results and Discussion

3.1 NON-REACTING FLOW

In order to analyse the effect of multistep injection to the behavior of the mixing jet, the mixing experiments in the cold flow field were subdivided into two parts, single- and multistep fuel injection.

The singlestep injection dealt with the dependency of the fuel/air mixing process on a four hole injector with an injection angle of 90°. This singlestep injection took place up stream of the first rearward facing step.

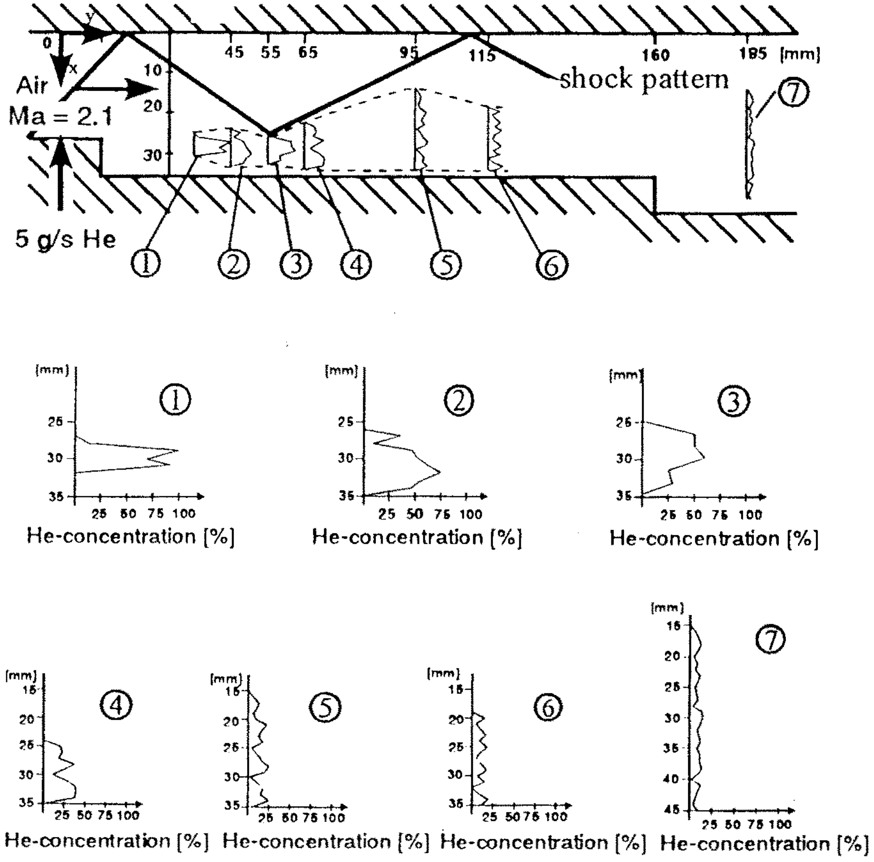

Fig. 2: Influence of shock waves and rearward facingsteps on the concentration profile in the mixing jet (Ma = 2.1; m_{He} = 5 g/s)

Multistep injection, meaning the simultaneous injection of fuel upstream of the first and second rearward facing step, was used to gain a higher mixing rate and a greater thickness of the mixing jet compared with the singlestep injection due to additional vortices in the wake of the jet.

3.1.1 Singlestep Fuel Injection

Figure 2 shows the concentration profile of the helium/air mixing jet to demonstrate the influence of shock pattern and cascades of rearward facing steps on the mixing jet. The helium mass flow was 5 g/s. The location of the shocks was taken from shadowgraphs. The concentration profile of the mixing jet was measured by means of Raman spectroscopy [20-22]. It can be seen that the helium/air mixing jet is strongly deformed by the influence of the oblique shock waves. The collision of the reflected shock with the mixing jet leads to a compression of the mixing jet at position 3. After the collision point the helium/air mixing jet expanded extremely due to local gradients

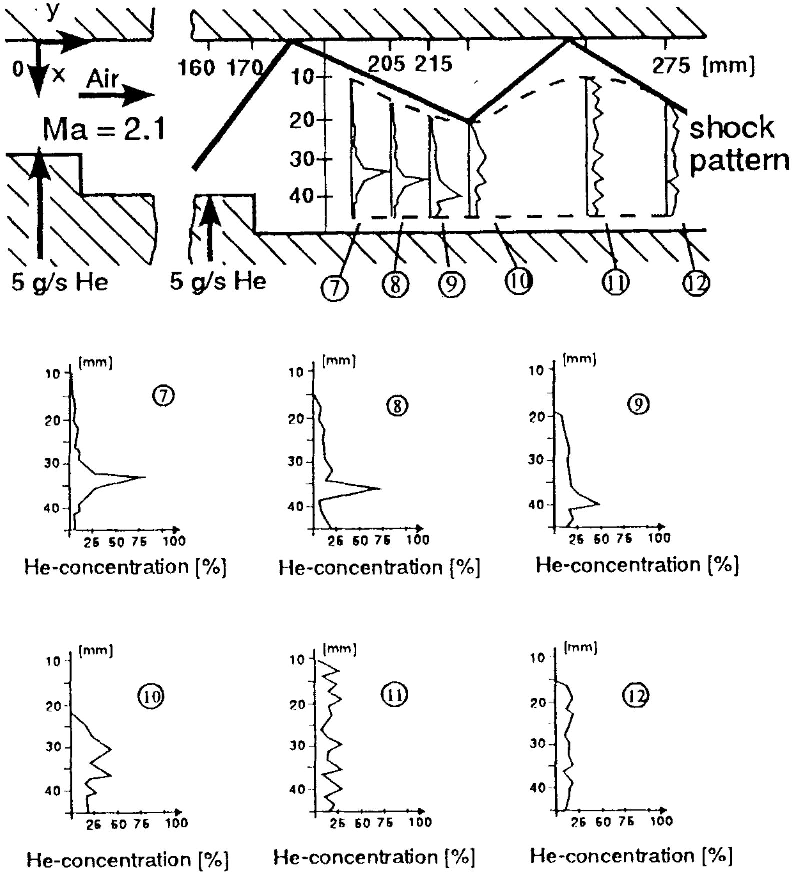

Fig. 3: Influence of multistep injection on the concentration profile in the mixing jet (Ma = 2.1; m_{He} = 10 g/s)

in the air flow which are originated by the oblique shock wave. This means that downstream of this point the mixing rate was very high. Large scale vortices in the wake of the second recirculation zone which were induced by the flow around the rearward facing step caused additional turbulent structures in the helium/air mixing jet. This leads again to a strong increase in the mixing rate and to a bigger mixing jet.

3.1.2 Multistep Fuel Injection

To gain higher mixing rates and a higher penetration of the mixing jet a multistep injection system was used to increase the turbulence-induced convective mass transfer in the mixing jet. Figure 3 shows the concentration distribution in the mixing jet which was originated using multistep injection. Here the total mass flow rate of helium was 10 g/s. Comparing figure 2 with figure 3, it can be seen that the multistep injection causes a higher penetration and a greater thickness of the mixing jet in the wake of the second rearward facing step. This was caused by large scale vortices and an additional impact momentum perpendicular to the air flow due to the second fuel injection. Figure 4 depicts the turbulent structure of the mixing jet which was investigated using Rayleigh scattering as measurement technique. Due to the short laser pulse duration of ca. 6 ns even high transient turbulent flow structures were frozen [20-22]. In this picture vortices which are originated by the second fuel injection and the flow around the second facing step can be observed. This indicates

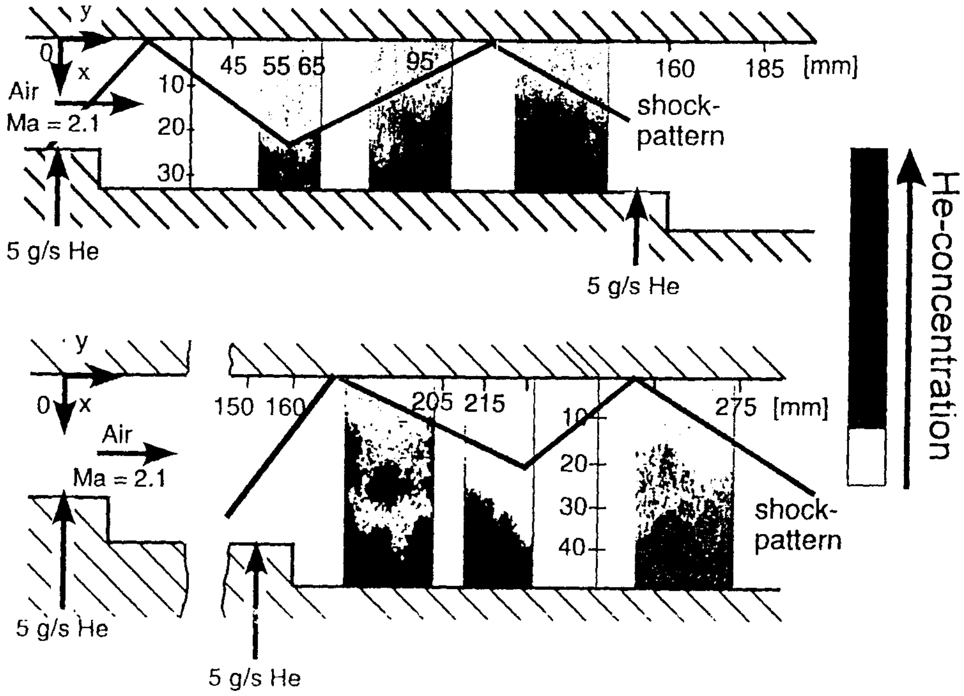

Fig. 4: Turbulent structure of the mixing jet (Ma = 2.1; m_{He} = 10 g/s)

that in the wake of the second rearward facingstep the mixing process was fundamental supported by turbulent structures in the flow field.

The influence of shock patterns on the development of the mixing jet is approximately the same as for the single step injection.

3.2 REACTING FLOW

3.2.1 Singlestep Fuel Injection

Figure 5 shows the turbulent flame structure in the wake of the first and second recirculation zone recorded by means of laser induced fluorescence. Here hydrogen was injected upstream of the first rearward facing step. The mass flow rate was again 5 g/s. This Figure depicts that the stabiliziation zone of the flame is located in the free shear layer which separates the mixing jet and the wake of the first rearward facing step. There are the greatest gradients of the velocity and thus there are the highest degrees of turbulence in this shear layer which enhance the mixing process and the flame stabilization. The increasing OH-concentration downstream of the first rearward facing step indicates the increase of the reaction rate in the flame due to turbulence induced mass transfer.

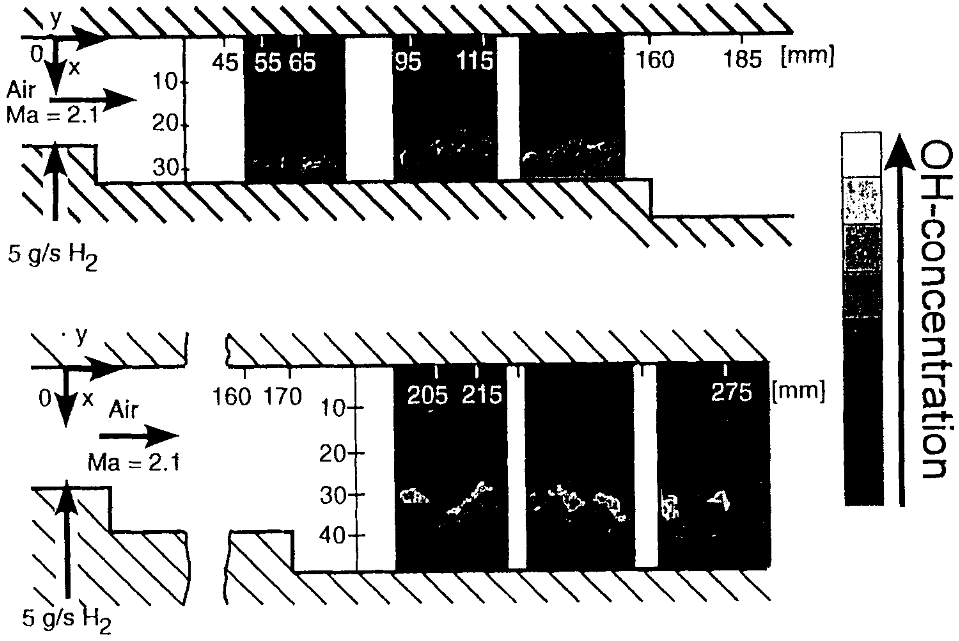

Fig. 5: Turbulent structure of the flame (single step injection, Ma = 2.1; m_{H_2} = 5 g/s)

The second rearward facing step induced additional turbulent structures in the mixing jet in the wake of the second recirculation zone. This led to an increase in the rate of chemical reaction indicated by the strong increase of OH-concentration in the flame (fig. 5 bottom). Figure 5 also shows that due to the additional turbulence the flame penetrated deeper into the surrounding air flow in the wake of the second rearward facing step. The wavy structure of the flame in the wake of the second rearward facing step was caused by the high intensity of turbulence in the mixing jet which enhanced the combustion process.

3.2.2 Multistep Fuel Injection

To gain shorter flame length and higher fuel efficiencies multistep fuel injection was used to generate turbulence in the reaction zone of the flame to increase the reaction rate and to stiring-up the combustion process. Figure 5 shows the structure of the flame and the OH-concentration distribution in the reaction zone in the wake of the first and second rearward facing step. Hydrogen was injected upstream of the first and second rearward facing step with a total mass flow rate of 10 g/s. The influence of the second fuel injection on the flame structure can be seen in the wake of the second rearward facing step. Due to large scaled vortices induced by the second injection the rate of chemical reaction has been increased. This was indicated by the increase in OH-concentration in the reaction zone. Comparing figure 5 with figure 6 it can be seen that the flame penetrated deeper into the surrounding air flow in the wake of the second rearward facing step. In the mixing jet the reaction zone was more broader than in the singlestep injection experiments caused by the higher intensity of

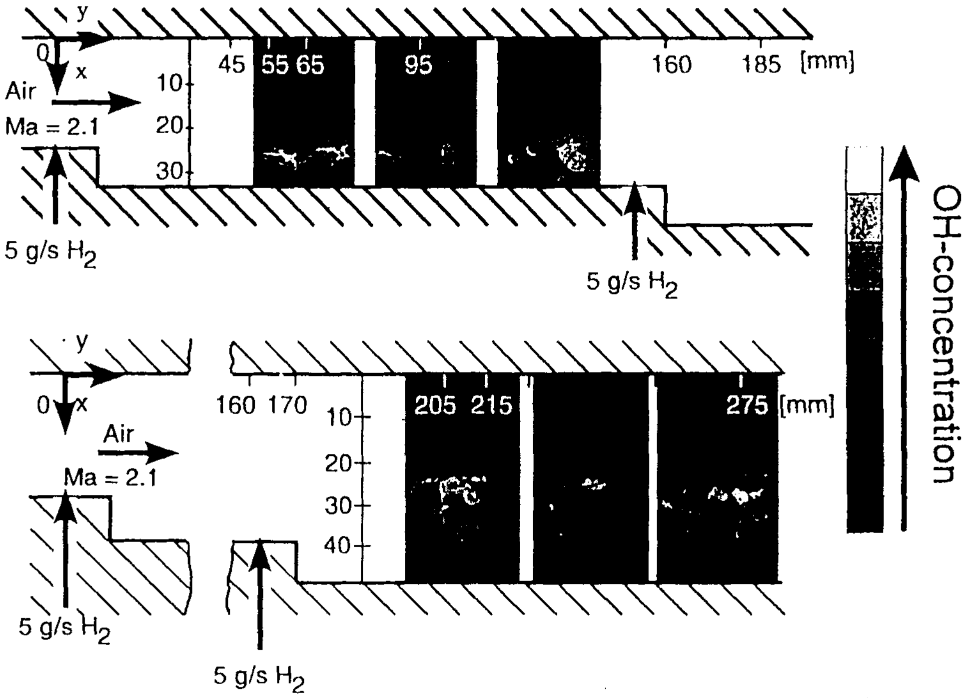

Fig. 6: Turbulent structure of the flame (multi step injection, Ma = 2.1; m_{H_2} = 10 g/s)

turbulence. All experiments have shown that multistep fuel injection in addition with rearward facing steps provides excellent mixing rate and an increase in the rate of chemical reaction. Thereby it was possible to achieve a short flame length and the conditions of flame stabiliziation.

4. Conclusions and Outlook

A multistep combustor with cascades of rearward facing steps and a multistep injection system was used to investigate the influence of the injector system and the rearward facing steps on the mixing and combustion processes in sub- and supersonic air flames. These experiments were conducted by means of non-intrusive optical measurement techniques. The results showed that oblique shock waves and turbulent structures in the flow field enhance the mixing and combustion processes. The application of multistep injector and rearward facing steps which induces turbulent structures in the reaction zone of the mixing jet led to an increase in the mixing rate and to a stiring-up of the combustion process. Furthermore by the use of multistep fuel injection it was possible to achieve short flame length.

This work will be continued by detailed investigation about the velocity distribution in the flow field and in the wake of the recirculation zones using two beam laser Doppler velocimetry. Furthermore it is planned to measure the major species concentration in the flame and in the exhaust to calculate the combustion efficiency.

5. Literature

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