APPLICATION OF SPONTANEOUS RAMAN SCATTERING TO THE FLOWFIELD IN A SCRAMJET COMBUSTOR

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Introduction

The weight of the oxidizer dominates the take-off weight of rocket based propulsion systems. Therefore, airbreathing engines that consume the oxygen from the atmosphere offer a promising alternative. At flight conditions with Mach numbers above 6 SCramjet propulsion systems represent a better suited concept than ramjet systems, as the high static temperature resulting from the deceleration to subsonic speed in ramjet combustors leads to the dissociation of the air and to thermal problems in the engine.

For the investigation of the ignition and reaction of fuel injected into the combustor of a SCramjet at a flight Mach number of 8 high temperature test air at supersonic speed is required. One economic possibility to simulate these inlet conditions experimentally is the use of vitiators, which preheat the air by the burning of hydrogen. Downstream of the precombustor the flow is accelerated in a Laval nozzle to a Mach number of 2.15 and enters the combustor.

For the numerical simulation of a supersonic reacting flow precise information concerning the physical properties during ignition and reaction are required. Optical measurements are best suited for delivering this information as they do not disturb the supersonic flow like probes and as their application is not limited by thermal stress. Raman scattering offers the possibility of measuring the static temperature and the concentration of majority species.

Experimental Setup

The model SCramjet combustor used for the experimental investigations is shown in Figure 1. The test air can be supplied with pressures up to 10 *bar*, which corresponds to a mass flow of cold air of approximately 1000 *g/s.* The total temperature can be increased up to 1400 *K* by means of a preheater. During experiments the total pressure in the preheater was 7.5 *bar* and the mass flow of the hot air approximately 300 *g/s*. In order to compensate for the oxygen loss, the test air is enriched with oxygen. The preheated flow is expanded in a Laval nozzle with a fixed geometry to a Mach number of 2.15 and enters the combustion chamber with an inlet cross-sectional area of 27.5 *mm* $\times$ 25 *mm*. At a distance of 75 *mm* downstream from the inlet plane the hydrogen is injected by means of exchangeable struts. The mass flow of the injected hydrogen can be varied up to 2.3 *g/s* by increasing the injection pressure. 140 *mm* downstream of the entrance, the flow in the combustion chamber is expanded from 27.5 *mm* $\times$ 25 *mm* to 41.5 *mm* $\times$ 25 *mm* with an angle of 4° in order to prevent thermal choking [1]. The front and the back side of the combustor offers optical access via quartz windows as illustrated in the right sketch of Figure 1. The side walls are constructed from stainless steel as single elements to avoid cavities resulting from manufacturing or mounting tolerances, which would cause severe disturbances of the supersonic flow. Directing the high-energy laser pulse through quartz windows appeared to be very difficult with respect to the maximum energy density for quartz glass without damage. This upper limit is particularly critical when using a lens with a long focal length to avoid breakdowns of the gaseous medium during the laser shots. Furthermore, the quartz windows tended to contaminate quickly and thus prohibited a precise detection of the weak Raman signal. In order to overcome this difficulty, both side walls are equipped with orifices (diameter 2 *mm*, axial distance 14.4 *mm*) in the middle plane at the same longitudinal coordinates. In order to minimize the influence of a potential leakage, all orifices are closed gas-tight except for the pair through which the laser beam is directed into the flow.

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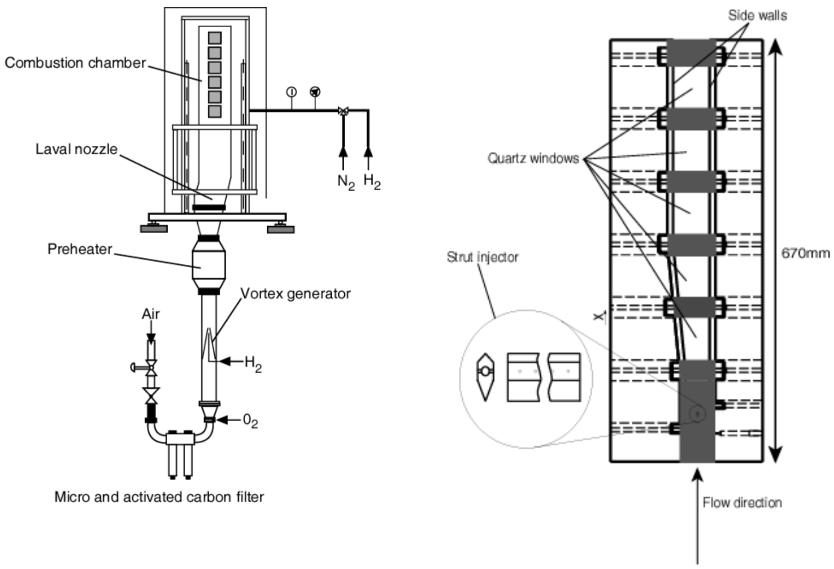

Figure 1: Experimental setup

The strut injector that was used in the numerical and experimental investigations is shown in Figure 2. It extends over the entire depth (25 *mm*) of the channel. The wedge-shaped cross section of the strut forms an angle of 45° at its leading edge and an angle of 90° at its trailing edge. The fuel injection occurs perpendicular to the main air stream through three orifices on each side of the strut with a diameter of 0.4 *mm*. The orientation of the hydrogen jets relative to the air stream is depicted in Figure 2.

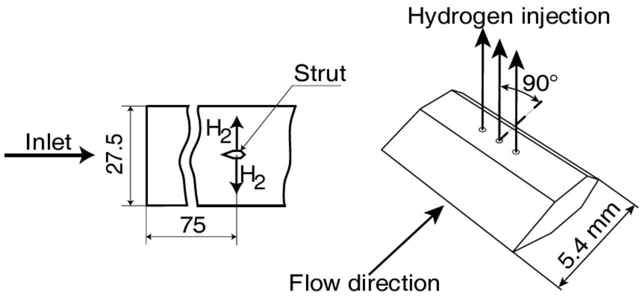

Figure 2: Strut injector

Results and Discussion

The knowledge of the static temperature is indispensable for the understanding of a reacting flow. As the application of intrusive techniques to a supersonic flow has serious effects on the flow structure and therewith on the ignition and reaction behaviour, only non-intrusive techniques e.g. laser-based techniques were used in the study. Furthermore, the high temperature and mechanical stress cause severe problems for mechanical probes and do not permit their use in the present situation. With the application of Raman scattering the static temperature and the concentration of the majority species in the flow can be measured. Raman scattering is an inelastic scattering process, which means that the light emitted from the molecules in the gas mixture is frequency shifted from the laser light. On one hand this offers the possibility of multispecies detection if the emitted light is resolved spectrally, on the other hand the Raman scattering is very weak (about three orders of magnitude lower than the elastic Rayleigh scattering [2]), which complicates quantitative experiments enormously. The scattered Raman power P_r can be expressed as

$$P_r = P_i n \left(\frac{\partial \sigma}{\partial \Omega} \right) \Omega l \varepsilon \,, \tag{1}$$

where P_i denotes the incident laser power flow, n the number density of scattering species, $\left(\frac{\partial \sigma}{\partial \Omega} \right)$ the differential Raman cross section, Ω the collection solid angle, l the sampling length and ε the collection efficiency of the optical system [2]. As it is shown in Equation 1, Raman scattering permits the measurement of the concentration n of majority species in hydrogen combustion like O_2, N_2, H_2O and H_2, if the laser power flow, the differential Raman cross section, the collection solid angle, the sampling length and the collection efficiency of the optical system is known from calibration measurements.

As the population of rotational and vibrational energy levels of the molecules is temperature dependent, the Raman scattering can also be applied for the measurement of the static temperature. If both the Stokes- and the Anti-Stokes line of one inert species in the gas mixture are intense enough, the static temperature T can be calculated from the following equation:

$$T = \frac{h \cdot c \cdot \Delta \nu}{k} \left(\ln \frac{I_S}{I_{AS} \cdot C_T} + 4 \ln \frac{\nu_0 + \Delta \nu}{\nu_0 - \Delta \nu} \right)^{-1} \,, \tag{2}$$

where h denotes the Planck's constant, c the speed of light, $\Delta \nu$ the molecule specific Raman shift, k the Boltzmann's constant, I_S and I_{AS} the intensity of the Stokes and the Anti-Stokes line respectively, C_T the calibration constant, which takes into account the efficiency of the optical setup and ν_0 the frequency of the laser light. In the current work the intensity ratio of the Stokes and the Anti-Stokes line of nitrogen was exploited. As thereby the spectral resolution of single branches is not required whereas a large spectral range has to be covered, a high signal intensity is obtained compared to the methods, which merely focus on single vibrational or rotational lines. For the Raman measurements a Nd:YAG laser (Quantel YG 782 C 10) with a wavelength of 532 *nm* and a pulse energy of approximately 1 *mJ* was used. The focal length of the focusing lens was 1000 *mm*. The scattered light was filtered with a Notch filter, in order to suppress the elastic scattered light, which would inhibit the detection of the comparatively weak Raman scattered light. The spectra was analyzed with a spectrograph (Acton Research, SpectraPro-275) and an intensified CCD camera (Princeton Instruments, ICCD-576 S/B). The investigated points were located at a distance of 166, 266, 366, 466, 566 and 690 *mm* from the combustor inlet and in the middle plane of the channel. The last studied point resided 20 *mm* downstream of the combustor exit plane. The total temperature in the preheater was 1150 *K* and the static injection pressure 12 *bar*, which corresponds to a hydrogen mass flow of 2 *g/s*. The Raman signal from 50 laser pulses was integrated. As the reflected light of the laser beam inside the combustor was very intense, i.e. the signal from oxygen at 580 *nm* was very close to the elastic scattered light at 532 *nm*, the examination of the spectra was restricted to the determination of the static temperature. The results of these measurements are shown in .

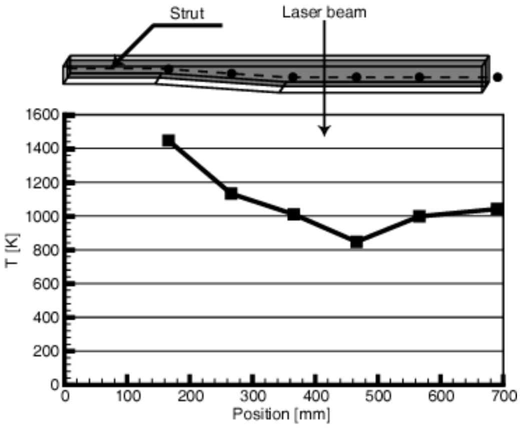

Figure 3: Static temperature along the combustor

It can be seen that the static temperature has its maximum of 1450 *K* at 166 *mm* behind the entrance of the combustor, which was the first optically accessible test point. Obviously, the reaction started right after the injection of the fuel. The leading edge of the strut produces a distinct shock wave, which is reflected at the boundary layer of the combustor side walls and causes the rise of the static temperature and pressure. The conditions for the self-ignition of the injected hydrogen are fulfilled and the reaction is stabilized immediately in the wake of the strut. Further downstream the static temperature decreases due to the divergent geometry of the channel. The minimum of the static temperature is 850 *K* at a distance of 466 *mm* from the combustor inlet. A continuous increase of the static temperature up to 1040 *K* at a distance of 20 *mm* downstream of the combustor exit plane (690 *mm* away from the combustor inlet) was observed. This effect is caused by the shock wave system emanating from the kink in the combustor side wall. As detailed data from the area immediately after the strut was not obtainable by the experimental setup, the ignition behaviour of the injected hydrogen was investigated by numerical simulations, which are described elsewhere [3].

In order to get information about the progress of the reaction within the combustor, static temperature and species concentrations were measured via Raman spectroscopy also at the axis of the exit cross section (41.5 *mm* × 25 *mm*) at an axial distance of 9 *mm* downstream of the exit plane above the end of the combustor. The origin of the coordinate system (Figure 4) is the front wall of the combustor. The points were chosen at –3, 3, 7 and 12.5 *mm*, the results at the other illustrated positions were expected to be symmetric to the center line at 12.5 *mm*. Their distribution is schematically shown in .

The optical setup and the experimental conditions were the same as in the previous investigation. The results of these measurements are shown in Figure 5.

It can be seen that hydrogen is still present at the exit of the combustor, particularly in the center of the flow. The concentration of the oxygen has its minimum in the center of the cross section, which indicates that the reaction is limited to the inner flow. Accordingly, the static temperature and water concentration have their maximum there. From the results of the Raman measurements it can be seen that the reaction of the fuel is quenched by the expansion of the combustor, which causes a decrease of the static temperature. The temperature and pressure measurements along the channel indicate that thermal choking does not occur within the flow. The second finding is that nearly no lateral mixing of the fuel with the test air occurs within the flow. This is due to the location of all injection orifices close to the center of the flow (Figure 2) and due to the lack of secondary flows in the combustor.

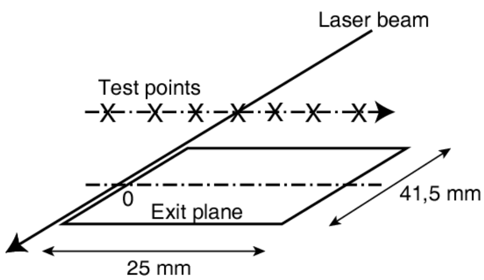

Figure 4: Distribution of test points

Conclusions

For the optimization of the burnout in SCramjet combustors the understanding of the ignition and the reaction of the injected hydrogen is inevitable. Optical measurement techniques are preferred as investigation tools because of their non-intrusive character and their applicability to the present hostile environment. For the simulation of the inlet conditions of a flight with a Mach number of 8 a hydrogen preheater and a Laval nozzle was used, which enabled the preheating of the test air up to 1400 *K* and the acceleration to a fixed Mach number of 2.15. In the current work Raman scattering was applied for the measurement of the static temperature and the concentration of the majority species in the supersonic reacting flow.

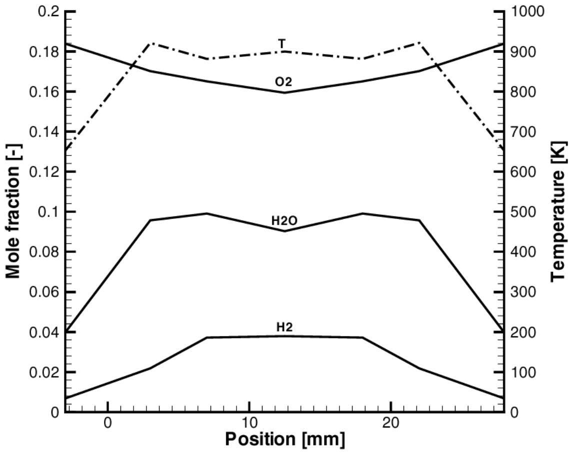

Figure 5: Temperature and species concentration at the exit of the combustor

From the Raman measurements it is evident that great care has to be taken in designing the cross sectional area of SCramjet combustors. Expansion avoids thermal choking but can also quench an already initiated reaction. The design of the fuel injector as well requires experience, as only a few milliseconds are available for the ignition and the reaction of the fuel within the combustor. Thus, the injector has to initiate self-ignition and to provide enough fuel air mixing. Both tasks lead to losses of total pressure and thus to a decrease of the engine efficiency.

The investigated injector was designed primarily for the generation of validation data for numerical calculations of the ignition zone near the strut. Since large amounts of hydrogen were measured at the exit of the combustor, it must be concluded that this type of injector provides insufficient lateral mixing for a technical application.

Furthermore, it was shown by the simulation of the flowfield around the strut that the ignition of the fuel is caused rather by the loss of total pressure and the increase of static temperature than by the induced shock wave system [3].

It has to be mentioned that the numerical investigation of a injector segment showed no stable reaction of the fuel under the investigated conditions, while in the experiment a stable flame was observed. This mismatch of the numerical and experimental results can be explained either with an additional shock wave system that is induced at the intersection of the strut with the walls, which promotes the ignition and which is neglected in the segmentwise calculation of the flowfield, or by the presence of reaction intermediates from the preheater.

Further experimental studies will focus on the investigation of the reaction in the preheater, on the optimization of the injector and the combustor design.

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