Analysis of flame characteristics in a scramjet combustor with staged fuel injection using common path focusing schlieren and flame visualization

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ABSTRACT

We conducted a comprehensive set of combustion experiments in a connected tube test facility to investigate the interface between supersonic and dual-mode combustion in a scramjet combustor. This is achieved using a staged injection scheme consisting of a strut as first stage and wall rams as second stage. Wall pressure measurements, flame visualization and focusing schlieren imaging are applied simultaneously to gain information on the flow field and the reaction zone. These combined data sets allow the analysis of the interaction of the supersonic main flow with the combustion zone. Stable and distinct flame states are identified at this interface, which are generally described rather unspecific in literature. These states differ in terms of flame structure and local shock pattern in the reaction zone, but cannot be distinguished solely by evaluating the static wall pressure distribution. Therefore, the present study also shows the limits of wall pressure measurements as only criterion for the classification of scramjet combustion phenomena.

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1. Introduction

Within a scramjet vehicle the engine is the most critical component. A stable, supersonic combustion process is desirable to ensure an efficient operation of the engine at high flight Mach numbers. This can be achieved by means of a suitable combustor geometry and fuel injection strategy. Therefore, the type and the geometry of the injectors as well as the number of injection stages are widely investigated topics. Many studies found in literature investigate fuel injection via port holes or rams located at the combustor wall, often with additional cavities to support flame stabilization and favorable ignition conditions [1–4]. Strut injectors are better suited, as they are the only effective way to inject fuel directly into the center of the flow [5–7]. By choosing a more complex strut geometry, mixing can be enhanced considerably as well. Examples for this kind of injection are the Hypermixer at JAXA [8,9], the strut investigated by Gaston et al. [10,11], or the injector investigated within the frame of the German Research Training Group GRK 1095 [12,13].

For any injection scheme, a main target is to achieve a stable, complete and efficient combustion while at the same time minimizing the length of the combustion chamber. During the acceleration phase of a vehicle up to cruise flight condition the engine must adapt to different operating conditions. For high cruise Mach numbers, it is desirable to maintain supersonic flow through the engine, while during ascent and descent phases the engine must operate at lower flight Mach numbers. This may result in ramjet mode, where the combustor flow is subsonic. In order to accommodate to this range of conditions, dual-mode operation of a single engine was pursued for instance during the HRE [14] and ESOPE [15] programs. As the influence of the operation mode on the performance of the vehicle is critical, ground testing is required to characterize the engine.

In addition to the engine inlet conditions, combustor characteristics such as geometry and amount of fuel can be varied to achieve different operation points. Masumoto et al. [16] varied the flow total temperature and the combustor length for wall injection. The resulting combustion regimes were characterized based on the static wall pressure distribution along the combustor symmetry plane. They identified dual-mode combustion featuring a pre-combustion shock train and supersonic combustion without any pressure rise upstream of the injection point. The scramjet regime was further divided into weak and strong combustion modes, which differ significantly in terms of flame position and heat release. The static wall pressure was also used as main criterion to distinguish combustion modes by Yan et al. [17]. They derived a classification similar to [16], although a slightly
different nomenclature was used to describe the same characteristic features. Within their study fuel equivalence ratio and injector geometry were varied for different inlet Mach numbers with ethylene and hydrogen as fuel.

Flame holding devices, e.g. a plasma torch [18], can extend the range of stable operating conditions. Bonanos et al. [18] presented a comparison for ethylene and hydrogen fueled combustion. The authors distinguished between scramjet and dual-mode combustion as a function of equivalence ratio and the total flow temperature to include off-design conditions. As an alternative, flame holding can also be supported using cavities integrated into the combustor walls downstream of the fuel injection. An example for cavity-based flame holding is given by Jeong et al. [19]. Ignition and flame position were again identified based on the wall pressure distribution, but further supported by laser induced fluorescence (LIF) measurements. Effects of fuel staging were investigated for the HiFiRE [20] combustor by Cabell et al. [21]. Similarly to Masumoto et al. [16], they defined combustion mode envelopes, but here as a function of the equivalence ratios of the first and second injection stages.

A corresponding mode characterization can be applied for strut injection based on the static wall pressure distribution. However, this is more challenging as combustion occurs in the center of the flow rather than near the wall, where the pressure ports are located. Rocci-Denis et al. [22] investigated mode transition from supersonic to subsonic as a function of equivalence ratio and fuel injection pressure. For the intermediate region, Dessornes and Scherrer [5] reported an additional, transonic mode based on the experimental wall pressure distribution in combination with numerical simulations. More recently, Zhang et al. [23] emphasized the need for a more detailed classification of combustion modes in strut-based scramjets. They also based their characterization on the work of Masumoto et al. [16] for a variation of hydrocarbon fuel equivalence ratios. Non-linear mode changes and critical equivalence ratios were identified based on a sudden change in wall pressure and one-dimensional analysis.

Zhang et al. [23] conducted their study for single-stage injection, which is limited in terms of maximum equivalence ratio and is prone to an abrupt change from supersonic to subsonic combustion. The effect of a second injection stage was included by Ueda et al. [24] in addition to a boundary layer bleed system upstream of the injection. Previous work on the strut investigated within the present work was done by Scheuermann et al. [25], who established a similar characterization for a single-stage concept. This was extended by Vellaramkalyil et al. [26], who added a wall-bound injection as second stage.

While most studies found in literature focus on the general mode characterization, little is reported on the features directly at the mode interfaces. Instead, a focus is often laid on the change from scramjet to ramjet operation, which is either investigated generically on a large scale or to observe transient phenomena during the entire transition process. For example, Sullins [27] increased the fuel equivalence ratio over test time to achieve mode transition towards ramjet operation. Similarly, Fotia [28] reported a transient mode change caused by boundary layer separation and shock formation when increasing the amount of fuel. By varying the combustor wall temperature, an oscillation between scramjet and ramjet mode could be realized, but without stable states in between both modes. The present study focuses on the detailed evaluation of the interface between supersonic and dual-mode combustion. This is especially relevant for engines operating over a wide range of Mach numbers, for example by using a variable geometry [29]. Here, the formation of subsonic flow regions inside the combustor may allow the flame to propagate upstream of the initial fuel injection. As a result, the thermal loads onto the structure, e.g. a strut injector, can change considerably, which outlines the importance of the investigation of this interface not only for combustion analysis, but also with regard to thermal management requirements [30]. As this regime is dominated by complex interactions between the flow field and the combustion zone, a sophisticated combination of several measurement techniques is obligatory to obtain all relevant data simultaneously. Different measurement techniques have been combined already in the past to extend wall pressure data for combustion diagnostics. Examples for the visualization of the flow field itself are shadowgraph [31] and schlieren [32,33] imaging as well as particle image velocimetry (PIV) [34].

In addition, imaging of the natural flame emission either in the visual range [32] or in the ultraviolet range – e.g. OH* chemiluminescence [2,31] – are often used to identify reaction zones. More sophisticated techniques like LIF [31,35] employ laser radiation to excite gas molecules and force species-dependent emission to provide a more detailed and spatially resolved insight into the combustion process. Flame structures were visualized for instance by Do et al. [36] and Brieschnek et al. [37], who used a combination of schlieren imaging and OH-PLIF for the investigation of artificial ignition devices and flame holding in supersonic flows. Resolving such flame phenomena is relevant for the present study, since changes in flame structure are seen as a direct indicator for an impending change in combustion mode. The suitability of such a combined measurement approach was further demonstrated by Laurence et al. [38], who used a setup consisting of fast response pressure taps, schlieren imaging and OH* chemiluminescence. However, their work focused on the evaluation of the transient interaction between heat release and shock train position inside a scramjet combustor rather than resolving a change in combustion mode.

In this study we combine static wall pressure measurements, which are regarded as the standard tool, with visual and schlieren imaging of the main reaction zone. Due to the use of a long-duration, clean air facility, a focusing schlieren system must be used instead of a standard setup to minimize the aberration caused by the hot windows. Using this measurement approach together with a fine-adjustable, staged injection concept, we are able to resolve the discrete, stable combustion states that form on the onset of the change from supersonic to dual-mode combustion. Each of these states is characterized by a distinct combination of features in flow field and flame.

2. Experimental methods

For experimental studies on high enthalpy flows, in general two types of test facilities can be distinguished. Shock tunnels and blowdown facilities are widely used due to their ability to generate the highest flow enthalpies. Furthermore, they are the only facilities in which entire engine configurations can be tested at realistic conditions for high Mach number flight. However, such facilities only allow a very short test time within fractions of a second. This makes it difficult to obtain steady-state conditions and to account for the effects of thermal inertia of the investigated structure. An alternative are long duration facilities, where energy is supplied continuously to the flow either via electrical heaters or by pre-combustion. However, chemical reactions are very sensitive to the presence of radicals in the flow and it is difficult to account for test gas vitiation effects. This is especially important when dealing with the investigation of accurate combustion mode determination. For instance, Goyne et al. [39] showed that vitiation supports supersonic combustion at higher equivalence ratios and thus leads to an overestimation of the ignition performance. A similar phenomenon was observed by Mitani et al. [40], where radicals in the vitiated test gas lead to premature ignition of the fuel. This effect can imply a reduction of the critical equivalence ratio by as much as 50% when
operating in a clean air facility. This evidently shows that vitiation effects are crucial for combustion studies. Therefore, the presented experiments are obtained in an electrically heated flow facility to allow the extrapolation of the results to flight conditions.

2.1. Experimental facility

The combustion test facility at the Institute of Aerospace Thermodynamics (ITLR) provides a dry, clean and heated air mass flow. Figure 1 shows an overview of the facility and its components. The air is supplied by a screw compressor, before being conveyed through an air dryer and into a three-staged electrical heater system. Thereby, maximum total flow temperatures of 1300 K at a total pressure of 6 bar can be realized without pre-combustion, which prevents any spurious radicals in the flow. This represents a flight condition of approximately Mach 5 at an altitude of 30 km, which is located within the typical flight regime for dual-mode operation. The heated air is then fed into the test section, where hydrogen is available as fuel for combustion experiments. An auxiliary air supply serves as reservoir for internal cooling of the injector.

Figure 2 shows a schematic view of the experimental model combustion chamber investigated at ITLR. It is manufactured from copper and water-cooled in order to withstand the high flow temperatures. The resulting wall temperature is constant at approximately 400 K. Optical measurements are conducted through quartz windows in the channel side walls (marked gray in Fig. 2). The temperature of the quartz windows is not measured, but is considered to be constant due to the long-duration experiments. This implies steady-state conditions with respect to the heat losses at the entire channel walls and ensures reproducible experiments for given inlet conditions.

The combustion chamber is divided into four segments: the first segment has a constant cross section, followed by a second section with a fixed opening angle of 1°. The last two segments feature variable opening angles, which are set to 2° for the present work. The combustor width is constant over the whole length at 40 mm, the height of the first segment is 35.4 mm. By using an exchangeable Laval nozzle insert flow Mach numbers ranging from 1.7 to 2.5 can be realized.

Table 1

<table>
<thead>
<tr>
<th>Feature</th>
<th>Start [mm]</th>
<th>End [mm]</th>
</tr>
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<tbody>
<tr>
<td>Strut injector</td>
<td>427.0</td>
<td>513.0</td>
</tr>
<tr>
<td>Optical window</td>
<td>500.0</td>
<td>585.0</td>
</tr>
<tr>
<td>Wall ramp injectors</td>
<td>675.5</td>
<td>698.0</td>
</tr>
</tbody>
</table>

(a) Lobed strut injector
(b) Wall ramp insert

Fig. 3. Fuel injectors.

Fig. 4. Numerical prediction of the mixing process downstream of the lobed strut injector, grayscale represents flow vorticity.

In total, 128 static pressure measurement taps are arranged along the top and bottom walls in the symmetry plane of the channel. The measurement rack consists of DSA3016 pressure modules manufactured by Scanivalve Corporation. The measurement uncertainty is within ±200 Pa for the pressure range of the experiments.

Table 1 summarizes the axial positions of all channel features, which are relevant for the present investigation. The model combustion chamber contains two fuel injection stages: a lobed strut injector is used as first stage and a symmetric wall-bound ramp configuration as second injection stage to consume oxygen left near the top and bottom combustor walls [13,41]. Figure 3 shows schematics of both injectors.

The strut injector extends over the whole channel width and is 86 mm long. It features a sharp, wedge-shaped leading edge up to mid-length, where the maximum height of 7 mm is reached. The lobed trailing edge has been designed to enhance fuel mixing by introducing streamwise vorticity into the main flow [42]. A similar feature has previously been used to enhance mixing in supersonic nozzles [43]. Its applicability for strut injection has been proven both experimentally and numerically in previous studies [12,13,26]. The overall flow field downstream of the strut injector is shown in Fig. 4 as predicted by a non-reacting CFD test case for the same main flow conditions as for the combustion experiments. It demonstrates the increased mixing of the injected fuel and the main flow through the streamwise vorticity induced by the strut and the wall ramps.

Figure 5 shows the trailing edge of the lobed strut injector in more detail. Fuel is injected into the main flow via five horizontal slots (marked gray in Figs. 3a and 5), all of which are 0.7 mm high. The three central slots are 9.2 mm wide, while the outermost slots feature a width of 4.6 mm. Small Laval nozzles are integrated near
structures is taken. The schlieren part and the nomenclature follows the design considerations of Weinstein [44,45] for a focusing schlieren system. A high-power LED (Huey Jann, green, 6200 lm) is used as extended light source. The field lens (\( f = 300 \text{ mm}, A = 92 \text{ mm} \)) focuses the light through the source grid and the combustion chamber onto the object lens. Here, a high quality prime lens with a focal length of 85 mm and a minimum aperture of f/1.4 is used. The schlieren edge is realized via a cut-off grid. The distances of the source and cut-off grids to the center of the prime lens are \( L = 640 \text{ mm} \) and \( L' = 98 \text{ mm} \), respectively. The image plane is located at a distance of \( l = 130 \text{ mm} \) with respect to the prime lens. The source grid features a clear aperture spacing of 2 mm printed on a transparent foil. The cut-off grid is made photographically.

For this purpose, the source grid is projected sharply through the object lens onto a high-contrast film (Ilford Delta 100). After development, the film is positioned at exactly the same location as for exposure. Creating the cut-off grid as exact image of the source grid accounts for the actual beam path used as well as for small aberrations of the optics. The schlieren image generated by this arrangement is then projected through a lens system consisting of a Fresnel lens and a second camera lens onto the photo chip of a Canon 600D camera.

The second part of the system allows to record the luminescence of the flame in the visual spectrum. To allow a proper comparison, the flame image must be taken simultaneously and at the same perspective. This requires a separation of flame luminescence and LED light along the common beam path of the system. A broadband 50/50 beam splitter is used to reflect light coming from the combustion chamber onto a secondary beam path. A second camera (Nikon D3) is then used to capture the flame images. A pair of filters suppresses light from the LED scattered at the optics and at the windows of the combustion chamber. A narrow line filter (±0.2 nm FWHM) is used to restrict the emission spectrum of the schlieren LED to 532 nm. This wavelength is then blocked for the Nikon camera by an additional notch filter (±4 nm FWHM). The use of a high-quality notch filter minimizes the spectral loss for the flame image. This approach was found to be superior to an analogous polarizer/analyzer configuration. Here, depolarization of the light as it is scattered of the chamber windows prevented an effective suppression.

Synchronized trigger pulses were sent to each camera once steady flow conditions were reached. Typical exposure times of 1/1000 s for the schlieren and 1/2 s for the flame image were chosen. These integration times are both an order of magnitude longer than the fluctuations of the flow field.

### 2.3. Image post processing

#### 2.3.1. Schlieren image post processing

The schlieren post processing is based on the approach presented by Kouchi et al. [46]. Two objectives are pursued, namely an enhancement of the schlieren structure, while in addition distortions by the optics are reduced.

For this purpose, the gray-scale schlieren image is first duplicated and then blurred using a Gaussian filter. By smearing all schlieren structures, the blurred image is a good approximation of the intensity distribution. An almost homogenous brightness is achieved by normalizing the schlieren with this reference image. This approach is chosen as obtaining a reference image at hot conditions is not possible without the main flow being active. The schlieren structures are then intensified by an edge-enhancement algorithm. Beside the desired enhancement of the flow structures, this procedure also emphasizes concentric circles projected from the last Fresnel lens. To reverse this unwanted feature, the image is transformed into its frequency domain using a two-dimensional Fourier transform. Here, the circles can easily be isolated by

The exit of the injection slots to minimize the velocity difference between fuel and main flow.

The wall ramp injectors are 215 mm long with a maximum height of 2.44 mm at the trailing edge. This corresponds to a ramp angle of 10°. Fuel is injected through 1.4 mm high and 6.9 mm wide slits (marked gray in Fig. 3b) at an angle of 15° relative to the combustor walls.

### Table 2

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( T_c [\text{K}] )</th>
<th>( \rho _c [\text{bar}] )</th>
<th>( M = u/c )</th>
<th>( T _s, \text{ext} [\text{K}] )</th>
<th>( \rho _s, \text{ext} [\text{bar}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main flow</td>
<td>1270</td>
<td>6</td>
<td>2.5</td>
<td>560</td>
<td>0.35</td>
</tr>
<tr>
<td>Fuel (1st stage)</td>
<td>300</td>
<td>7</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fuel (2nd stage)</td>
<td>300</td>
<td>7</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The optical setup illustrated in Fig. 6 combines two visualization techniques. Firstly, a focusing schlieren setup is used to visualize the flow field. Secondly, a visual image of the flame and its
Fig. 7. Comparison of raw (left) and processed (right) schlieren images taken directly downstream of strut injector.

exploiting their periodic shape. The fundamental frequency of the circles as well as their 2nd and 3rd harmonics are filtered without affecting any other information contained in the image. The filtered image is then transformed back to the spatial domain. For the last step, the contrast of image is enhanced by stretching the histogram of the image. The effectiveness of this procedure is illustrated in Fig. 7 for a non-reaction as well as a combustion case injecting air and hydrogen, respectively.

2.3.2. Flame image and additional post processing

The raw flame images still show minimal remains of the LED light. As notch filters are only effective for a small range of incident angles, stray light reflected mainly at the strut injector was not blocked entirely. This distortion is constant for all experiments, as the optical arrangement is not changed. Hence, a reference image taken without a flame and subtracted from all raw images is sufficient to remove this distortion.

Further post processing concerns scaling and positioning of both images. As both schlieren and flame images show the trailing edge of the injector, it is used as the reference of scale. For the combined illustration of schlieren and flames images, both images are superimposed as can be seen later, for instance, in Fig. 12. The transparency of the schlieren image is then modulated with respect to the brightness of each pixel. This means that darker schlieren structures remained visible while the gray background is more transparent allowing the flame to be seen.

3. Results

3.1. Depth of focus validation

Due to the continuous operation of the test facility, the quartz windows heat up and change their local refraction index. As a result, the smaller changes of refraction index of the flow induced by shock structures are blocked. In contrast to conventional schlieren, focusing schlieren allows to constrain the imaging to a focal region placed in the center of the flow. The depth of focus of the schlieren setup was experimentally verified by traversing a small schlieren object along the optical axis. For this purpose, a free jet approximately 1 mm in diameter was generated by forcing air at \( p_i = 6 \text{ bar} \) through a small pipe. This jet was then gradually moved out of the focal plane in direction of the optical axis (z-direction). Figure 8 illustrates the blurring effect of the technique. At the focal plane (\( z = 0 \text{ mm} \)), the shock system is sharply projected onto the camera chip, but it increasingly blurs as the jet is traversed out of the focal plane. For the experiments, the focal plane is placed in the symmetry plane of the combustion chamber. The combustor width extends to \( z = \pm 20 \text{ mm} \), followed by the 15 mm thick quartz windows. Consequently, Fig. 8a–c corresponds to the flow inside the combustion chamber, while Fig. 8d–e represents the window region. This sequence of images shows that – while flow information is collected throughout the majority of the chamber width – the window region is sufficiently blurred to block the negative influence of the hot windows.

The depth of focus is limited by the smallest aperture within the optical system. Technically, a smaller depth of focus down to \( \pm 5 \text{ mm} \) can be realized using the components of this setup as demonstrated in previous work [47]. However, the application at the combustion chamber limits the potential reduction. The imaging lens system formed from the Fresnel lens and the second camera lens is required to capture the entire window in a single image, but reduces the effective aperture of the object lens. For the presented work, the resulting larger depth of focus is actually beneficial as long as the windows are sufficiently blocked. Because the flame image represents a line of sight average, the schlieren image must also capture most flow features along the chamber width for a valid comparison. For the same reason, a small aperture field lens can be used instead of a large Fresnel lens as in [47], which was found to give a better contrast for the manufacturing of the cut-off grid. It should be noted that, if a minimal depth of focus is pursued, an additional constraint is given by the combustion chamber height. At some point, it acts as an additional aperture in the optical path.

3.2. Analysis of flame characteristics

Previous studies conducted in the combustion chamber investigated here [13,26] used the static wall pressure distribution as main criterion to characterize the combustion processes. An exemplary pressure distribution for a two-staged injection with \( \Phi_1 = 0.17 \) and \( \Phi_2 = 0.10 \) is shown in Fig. 9. The gray areas mark the positions of the strut injector and the wall-bound second stage, respectively. The combustion zone can be identified by comparison to the pressure distribution of a non-reacting air flow, i.e. \( \Phi_1 = \Phi_2 = 0 \). It can be seen that a significant pressure rise occurs
at around $x = 0.53 \text{ m}$, indicating the ignition of the first injection stage. Due to the divergent combustor duct the flow accelerates towards the outlet, which is represented by the declining static wall pressure downstream of the second injection stage in spite of reaction zones being present in this area. The pressure distributions at the top and bottom walls of the combustor are practically identical, which would imply a symmetrical flow field in the combustor. However, given the geometry of the strut injector, locally confined asymmetries in the center of the combustor are known to exist but cannot be resolved by the wall pressure. This is due to the pressure taps being located only at discrete positions along the combustor wall and already shows a drawback of this measurement technique. In the following only the pressure distribution along the top wall will be shown in case of symmetric measurements. Towards the exit of the combustor a shock train is formed by the accommodation of the supersonic channel flow to atmospheric pressure. An upstream influence of the shock train is present within the subsonic parts of the boundary layer. Furthermore, the higher static temperatures in this region also initiate ignition as shown by Makowka et al. [48]. However, this is observed for almost all combustion cases, but only represents the initial phase of the combustion experiment. It does not affect the resulting stable combustion type itself, which reproducibly depends on flow conditions and fuel equivalence ratio only.

As no pressure rise upstream of the strut is observed, the main flow stays supersonic until there. However, without further information it can only be concluded that the flame is attached to the trailing edge of the strut. For a more precise classification of the combustion, additional information is required. Therefore, a combination of both schlieren and visual flame images is evaluated together with the wall pressure measurements. The schlieren visualize the flow field, the flame image illustrates the main reaction zones and the static wall pressure provides additional information about main flow features and areas of heat release.

To identify the different combustion states a set of equivalence ratio combinations is tested. $\Phi_1$ is increased in steps of 0.01 starting at 0.15, while $\Phi_2$ ranges from 0 to 0.15 in steps of 0.05. Based purely on static wall pressure, already a preliminary classification of the test cases into four types can be obtained. Typical wall pressure distributions corresponding to this classification are shown in Fig. 10.

Type I. Shock train combustion (green): the pressure distribution indicates that reaction is only occurring in the combustor exit shock train.

Type II. Pressure rise at $x \approx 528 \text{ mm}$ (blue): the pressure distribution suggests a lifted flame, which begins upstream of the second injection stage.

Type III. Pressure rise at $x = 528 \text{ mm}$ (red): the pressure rise at the first pressure tap downstream of the strut indicates that the flame anchors at the strut injector. This suggests a supersonic main flow without upstream interaction, but does not allow a distinction between supersonic and subsonic combustion itself.

Type IV. Combustion with subsonic zones (yellow): a pressure rise upstream of the injection is found, which implies the existence of subsonic reaction zones upstream of the injector trailing edge. The pressure level shortly downstream of the trailing edge is increased significantly compared to type III.

The experimental conditions are designed such that all four types can be realized within the test matrix. The matrix boundaries are given by the appearance of subsonic combustion for high equivalence ratios and shock train combustion for lower equivalence ratios, respectively.

When considering additional measurement techniques, one would expect those results to coincide with this preliminary classification. For the present case, the visual flame image provides information about flame position and intensity of the combustion. The schlieren image allows an identification of supersonic and

![Fig. 9. Exemplary static wall pressure distribution.](image1)

![Fig. 10. Static wall pressure distributions at top wall for different combustion types.](image2)

![Fig. 11. Static wall pressure distributions along top wall for selected cases.](image3)
subsonic regions. For most of the experiments within the test matrix, the classifications based on the single techniques match. However, in some of the investigated cases the characterizations yield contradictory results. These mixed cases exhibit a combination of features of two combustion types, namely type III and type IV.

Figure 12 provides an overview of all investigated cases by means of an overlay of visual flame images and schlieren imaging. The cases are colored according to the preliminary classification presented above. The mixed cases are indicated by a striped border.

In the following, several cases are investigated separately in more detail, which are indicated by a white mark in Fig. 12. First, cases with a coinciding characterization of types II, III and IV are discussed to provide a basis for the evaluation of the mixed cases, which is conducted afterwards.

The corresponding static wall pressure distributions of these selected runs are presented in Fig. 11. The only case exhibiting a steep pressure gradient at the strut trailing edge is $\Phi_1 = 0.20/\Phi_2 = 0.05$, where the magnitude of static wall pressure increase reaches the level of a type IV case as shown in Fig. 10. The other extreme is provided by $\Phi_1 = 0.17/\Phi_2 = 0.05$, which does not feature a pressure rise directly at the injector trailing edge. The five remaining cases in between would be considered to be of type III if only the pressure distribution was investigated.

For each selected equivalence ratio, the schlieren image is presented together with an overlay of schlieren and visual images. Also the corresponding static wall pressure distribution is added.

![Fig. 12. Overview of investigated cases.](image-url)
for the sake of completeness and clarity. As mentioned above, only the pressure distribution along the top wall is shown unless asymmetries occurring within the flow field cause a deviation between top and bottom wall pressure.

3.2.1. Type II

For $\Phi_1 = 0.17/\Phi_2 = 0.05$, an undisturbed pattern of shock and expansion waves is visible in the schlieren image as presented in Fig. 13a. This pattern is caused by both the lobed geometry of the trailing edge and the supersonic fuel injection. It extends a significant length into the flow. However, reaction only takes place further downstream of the injector and outside of the field of view of the schlieren system. For this reason, the complete visual flame image is shown in Fig. 13d.

A thin, lifted flame in the center of the duct is observed. Together with the static wall pressure distribution, this suggests a supersonic flow through the combustor.

3.2.2. Type III

At $\Phi_1 = 0.15/\Phi_2 = 0.15$ and $\Phi_1 = 0.19/\Phi_2 = 0.05$, supersonic combustion is indicated by the pressure distribution. Furthermore, the flame is observed to anchor at the trailing edge of the strut based on visual imaging. For both cases, the schlieren imaging as presented in Figs. 14a and 15a still shows a clear pattern of shock and expansion waves originating at the strut trailing edge.

When superimposing the schlieren image on top of the visual image of the flame as shown in Figs. 14b and 15b, it can be seen that the shock system is present within the combustion region. Furthermore, it is observed that the flame front is coinciding with these discontinuities within the flow, as no upstream crossing of the flame across the trailing edge expansion fan (highlighted by the blue dotted lines) can be seen. Especially in Fig. 15b, ignition is found to occur at shock crossings directly downstream of the trailing edge due to the favorable temperature conditions in these flow regions.

Combined with the classification based on the static wall pressure distribution, the shock structures confirm that a supersonic combustion region at the trailing edge of the strut is present for these investigated equivalence ratios. No upstream propagation of flame and pressure rise can be observed, which is supported by the fact that the flame front is defined by the flow discontinuities originating at the trailing edge.

3.2.3. Type IV

In contrast to the supersonic flames discussed above, for $\Phi_1 = 0.20/\Phi_2 = 0.05$ subsonic combustion is suspected based on visual imaging and the static wall pressure. This is confirmed by the schlieren image shown in Fig. 16a. No shock or expansion waves are observed other than directly at the injection ports. Instead a subsonic wake structure appears at the trailing edge of the strut. If combined with the visual image of the flame as presented in Fig. 16b, it can be seen that no flame front anchoring is observed for this case, instead the flame clearly spreads over the whole cross section and reaction is already taking place upstream of the injection ports.

Based on the wall pressure rise shown in Fig. 16c, it is found that ignition occurs already at half length of the injector, which
corresponds to the beginning of the lobed part of the strut. Recirculation zones are formed inside the lobes, which then favor an upstream propagation of combustion due to higher static flow temperatures. Evidence for combustion zones inside the injector ramps is provided by local degradation of the surface, which is found by optical inspection of the strut after experiments. This phenomenon is more pronounced along the lower surface of the injector, which can also be deduced based on the asymmetric wall pressure distribution. This is caused by three lobes being present here compared to only two at the upper surface. Furthermore, the two lobes towards the channel walls are smaller in width. They support the creation of recirculation zones even further, as the boundary layers cause a relatively higher decrease in effective width of the lobe compared to the wider geometric features towards the center of the strut.

3.2.4. Type III 1/2

Within the test matrix also mixed cases occur for two equivalence ratios. These mixed cases differ from the flame types discussed above in such as one of the measurement techniques seems to contradict the others in terms of combustion classification. While the visual flame images indicate subsonic regions for both cases, either the static wall pressure or the schlieren image does not correspond to this finding.

The first example is found for $\Phi_1 = 0.16/\Phi_2 = 0.15$. As presented in Fig. 17c, the static wall pressure indicates a slight pressure rise on the bottom wall upstream of the strut trailing edge. However, according to the combined schlieren and visual imaging in Fig. 17b, the expansion fans seem to limit the reaction zone in upstream direction, which is a feature of type III. This is found to be misleading due to the limited field of view of the combined image. When considering the original visual image in Fig. 17d, where the whole combustor window is visible, a slight upstream propagation of the combustion region is observed along the lower surface of the strut. This region is not accessible by the schlieren system because of geometrical constraints due to the combustion chamber and the injection system. The flame propagation, however, is considerably weaker as compared to pure type IV, where it can already be clearly seen in the combined illustration in Fig. 12.

The main difference for the present case is that the schlieren image in Fig. 17a clearly shows the expansion fans downstream of the strut combined with a shock structure in the center of the flow. This is contrary to the classification of type IV, where no flow discontinuities are visible at all.

A similar phenomenon is observed for $\Phi_1 = 0.18/\Phi_2 = 0.10$, as shown in Fig. 18. Here, the visual flame image shows a pronounced recirculation zone underneath the strut, which corresponds to type IV. However, the static wall pressure along the combustor center line does not exhibit any pressure rise upstream of the trailing edge, thus indicating a type III combustion. When taking the schlieren image into account, a distinct shock structure at the trailing edge is visible. Furthermore, an additional feature compared to $\Phi_1 = 0.16/\Phi_2 = 0.15$ is found: While the expansion fan originating at the upper corner of the trailing edge coincides with the upstream flame front, the one originating at the lower corner is found to visibly influence the flame. A bulge in the flame contour coincides with the passing of the expansion fan through the combustion region.

This leads to the conclusion that not only the main flow is still supersonic, but also that supersonic regions exist inside the reaction zone. When considering the three-dimensional geometry of the strut injector, an even more detailed assessment of the investigated flow region can be obtained. As already discussed above, due to the smaller lobes at the lower injector surface near the combustor side walls flow separation is more likely to occur. Combined with the fact that the static wall pressure taps along the symme-
try plane of the channel do not register a significant pressure rise or none at all, it is presumed by the authors that for these mixed cases ignition takes place towards the sides of the combustor. The flame then spreads towards the center of the combustion chamber, where the schlieren images indicate supersonic flow and a clear pressure rise is registered.

The mixed combustion type is generally reproducible for the two equivalence ratio combinations presented above. Furthermore, Fig. 12 shows a clear, systematic distribution of the different stable states. It should be noted that this intermediate state is very sensitive to the equivalence ratio. Hence, a fine controlling mechanism is needed to adjust the fuel amount precisely. This is the reason that the mixed state is observed for $\Phi_2 = 0.15$ and $\Phi_2 = 0.10$, but not for $\Phi_2 = 0.05$. Here, the mixed state is again expected at $\Phi_1 = 0.195$ according to Fig. 12, but a resolution of 0.005 in first stage equivalence ratio is not feasible with the equipment used. It is suspected that the transition from type III to IV always includes a stable intermediate state, which exhibits combined features of both types.

### 3.3. Variation of flame characteristics with equivalence ratio of staged injection

A summary of the experimental results obtained for our test matrix is presented in Fig. 19 as a function of $\Phi_1$ and $\Phi_2$. The symbols represent the different combustion types observed for each experiment.

Two clear limits for the investigated combustor are observed: A lifted flame or shock train ignition only occurs for single staged injection at lower values of $\Phi_1$ and at low total equivalence ratios for staged injection. Analogously, an upper limit is defined, at
which the flame is found to be mainly subsonic. In between the transitional region is located, where the flame either anchors at the strut injector for type III or begins to show subsonic features. Furthermore, the potential of staged injection is evident as two different distributions of the same total equivalence ratio can yield completely different flame states. This can be observed at three values for $\Phi_{\text{tot}}$. The combinations yielding the same total equivalence ratio are marked by circles in Fig. 19.

- $\Phi_{\text{tot}} = 0.21$ (solid circles): for $\Phi_1 = 0.16$ and $\Phi_2 = 0.05$, a lifted flame downstream of the strut injector is observed, while single staged injection at $\Phi_1 = 0.21$ only results in shock train combustion.
- $\Phi_{\text{tot}} = 0.22$ (dotted circles): when increasing the first stage equivalence ratio from $\Phi_1 = 0.16$ to $\Phi_1 = 0.17$ at the same $\Phi_2 = 0.05$, staged injection only results in a lifted flame. However, the same total change for a single staged scheme to $\Phi_1 = 0.22$ results in a shift from one extreme to the other.
- $\Phi_{\text{tot}} = 0.25$ (dashed circles): even when comparing two combinations of staged injection of $\Phi_1 = 0.15$ and $\Phi_2 = 0.10$ and $\Phi_1 = 0.20$ and $\Phi_2 = 0.05$, a distinct change in operation mode can be realized when fuel is split differently between the two stages.

4. Conclusion

A detailed investigation of flame characteristics for a scramjet with a staged strut and wall ramp based injection scheme was conducted. The focus is laid on the interface region between supersonic and dual-mode combustion, where stable states with distinctive features are shown to exist.

While wall pressure measurements are valuable for a coarse classification of combustion types in terms of lifted, attached or subsonic flames, a finer characterization of flames anchoring at the strut is not possible. However, in combination with measurements obtained from different, simultaneous techniques, these 1D pressure measurements can be extended to provide deeper insight into the flow. This includes a focusing schlieren system, which is demonstrated to overcome the limitations of a conventional schlieren system when used at high-temperature, long-duration facilities with the resulting need for cooled combustor walls. Using these techniques, stable combustion states could be identified which were not observed so far. When using criteria established in literature, the majority of the investigated cases would be classified as supersonic in general. Within the present study, we show that local subsonic flame regions are gradually formed, leading to a stepwise transition from supersonic to dual-mode combustion. This behavior is found to be consistent for different total equivalence ratios, which shows that the stable intermediate states are a systematic feature.

By varying the equivalence ratios of both the first and second injection stage, an extensive test matrix was derived within the operational limits arising from no combustion and subsonic combustion, respectively. The given range of investigated conditions is condensed into a comprehensive combustion type classification for the investigated combustor. Within this illustration the expected benefit of fuel staging is also demonstrated, as different combustion types can be realized for the same total equivalence ratio.

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