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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 ramps 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.

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 ramps located at the combustor walls, 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

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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 Vellaramkalayil 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 Brieschenk 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 blow down 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