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Incipient thermal choking and stable shock-train formation in the heat-release region of a scramjet combustor. Part I: Shock-tunnel experiments

S.J. Laurence [a,*], D. Lieber [a], J. Martinez Schramm [a], K. Hannemann [a], J. Larsson [b]

[a] Institute of Aerodynamics and Flow Technology, Spacecraft Department, German Aerospace Center, Bunsenstr. 10, 37073 Göttingen, Germany
[b] Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA

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ABSTRACT

A series of experiments is performed in the High Enthalpy Shock Tunnel Göttingen to investigate the response of the HyShot II scramjet combustor to equivalence ratios close to the critical value at which the onset of thermal choking occurs. This critical equivalence ratio is first identified (for simulated Mach-8, 27-km altitude conditions) as 0.38–0.39. Subsequent experiments cover the range between this value and 0.50. As the HyShot II combustor has a constant-area cross section, the expected behavior in this equivalence-ratio range is the formation and upstream propagation of an unsteady shock train that would eventually lead to inlet unstart. Instead, however, the shock train is observed to become lodged in the heat-release zone of the combustion chamber, with a quasi-stable position that shifts upstream with increasing equivalence ratio; this behavior is distinct from the steady isolator shock trains seen in traditional dual-mode scramjet configurations. The shock-train development in the present experiments is characterized through fast-response surface pressure and heat-flux measurements, as well as simultaneous high-speed schlieren and OH* chemiluminescence visualization. Possible explanations for this unexpected behavior are proposed in terms of the increased heat-transfer to the combustor walls and a possible increased uniformity of heat release across the combustor cross-section caused by the presence of the shock train.

1. Introduction

Shock-train formation in scramjet flowpaths is typically encountered during mode transition in dual-mode configurations or, less desirably, at the onset of inlet unstart. Regarding the former, the dual-mode concept was proposed by Curran and Stull [1] to extend the lower-Mach-number operating range of scramjets: the crux of the concept is the inclusion of a constant-area diffusor, known as the inlet isolator, upstream of the combustion chamber. At lower flight Mach numbers, for which shock-induced total pressure losses are not so severe, the axial heat-release and area distributions in the combustion chamber are tailored so that the flow becomes thermally choked (i.e., reaches sonic conditions), leading to the formation of a normal shock train in the isolator with a subsonic core. At higher Mach numbers, the flow-path might be completely absent of shock trains if operating in pure scramjet mode. Alternatively, if the combustion-related pressure rise causes boundary-layer separation on the combustor walls, this may propagate upstream, forming an oblique shock train inside the isolator with a supersonic core [2]. Both normal and oblique shock trains can exist stably in the isolator over a certain range of operating conditions; if the back pressure exceeds a certain threshold in either case, however, the shock train will propagate further upstream and unstart the inlet.

Schematic drawings of normal and oblique shock trains in a scramjet isolator are shown in Fig. 1. The normal shock train is seen to take the form of a series of bifurcated normal shocks, the flow re-accelerating behind each of which (except the final, terminal shock) to supersonic conditions. In some observed cases [3,4], only the leading shock is bifurcated. The oblique shock train consists of a series of crossed oblique shocks that reflect from the isolator boundary wall layers as expansion waves. Oblique shock trains are typically associated with higher inflow Mach numbers than normal shock trains, above approximately Mach 2 [2,5].

* Corresponding author at: Department of Aerospace Engineering, University of Maryland, College Park, MD 20742, USA.
E-mail address: stuartl@umd.edu (S.J. Laurence).

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Stable isolator shock trains have been observed in dual-mode configurations by a number of experimental researchers. Typically, these observations are made indirectly through the measured pressure rise ahead of the injection location, e.g., [6–9]; but direct visualization of the shock train with schlieren [10] and interferometry [11], notably during mode transition, has also been performed. In order to study propagating shock trains in scramjet isolators, the approach generally taken is to employ a non-reacting flow and to replace the combustion-induced pressure rise with mechanical throttling or mass addition, e.g., [12–17]. This allows the use of cold-flow facilities and simplifies the implementation of diagnostic techniques; nevertheless, doubts have been raised by the analysis of Laurence et al. [18] concerning the suitability of this approach for simulating shock trains induced by thermal choking. Experimental measurements showing propagating shock trains in combusting flows, though more relevant, are more difficult and somewhat rarer [19–22].

In our previous work [18], we investigated the transient response of the HyShot II combustor to large equivalence ratios (typically 0.6–0.7) in experiments in a reflected shock tunnel. The shock train that formed was determined to result from localized thermal choking; after propagating some distance upstream, the shock train slowed and appeared to pause a few combustor heights downstream of injection. Because of the short facility test time, however, we could not ascertain whether this pausing was evidence of a new, stable flow topology. Since the combustion downstream of the leading shock continued to intensify, we speculated that it may simply be a transient configuration. A simple theoretical analysis predicted that the shock train should decelerate as it moved upstream in the combustor, but not terminate its motion completely.

In the present study, a series of experiments was carried out using the same simplified scramjet configuration (HyShot II), concentrating on equivalence ratios close to the critical value at which thermal choking and shock-train formation in the combustor first occur (approximately 0.4). These experiments revealed a behavior hinted at in our previous investigation: after the shock train formed towards the rear of the combustor and had propagated some distance upstream, it came to rest within the heat-release region of the combustor without further substantial upstream motion. This (quasi-)stable position varied strongly with the equivalence ratio. Similar behavior was discovered in numerical simulations performed in conjunction with, but independently from, the experiments. As this differs somewhat from the conventional dual-mode shock-train behavior documented previously in the literature, here we describe the experimental observations associated with this phenomenon and hypothesize about its origin; an accompanying paper [23] details results from the corresponding numerical simulations and provides a more complete physical analysis.

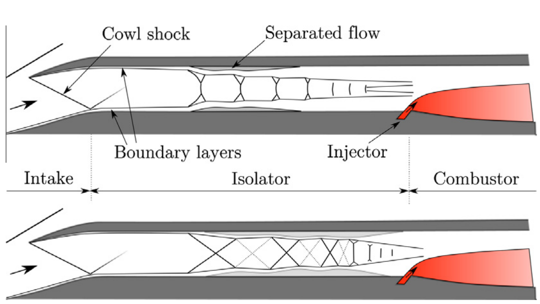

Fig. 1. Flow features within a scramjet isolator with (above) a normal shock train and (below) an oblique shock train present (after [2,5]).

2. Experimental apparatus

2.1. Facility

The experimental facility for this investigation was the hypersonic wind tunnel HEG (High Enthalpy shock tunnel Göttingen), operated by the German Aerospace Center (DLR). HEG is a free-piston-driven reflected-shock tunnel, capable of simulating a wide range of flow conditions up to re-entry type enthalpies and densities. Further details regarding the operating principles of HEG and the conditions achievable may be found in Refs. [24–26]. For the present investigation, a single low-enthalpy condition (nominal HEG Condition XIII) was employed. Condition XIII is intended to simulate Mach-8 flight at an altitude of approximately 27 km; compared to our previous study [18], a slightly modified version of the condition was used in order to extend the steady test period. The mean reservoir and free-stream conditions averaged over the entire campaign are tabulated in Table 1 together with associated single-run uncertainties. The measured quantities are the reservoir pressure, p_0, and the incident shock speed, from which the reservoir enthalpy, h_0, is calculated using a standard procedure [27]. The free-stream conditions are calculated from a numerical simulation of the nozzle flow; parameters such as the boundary-layer transition location and flow equilibrium state are tuned to match detailed calibration-rake measurements [24,28]. The free-stream uncertainties have been derived assuming the dominant error source to be the reservoir properties. The run-to-run variation (95% interval) in p_0 and h_0 over the campaign were 5.4% and 2.4%, respectively; the corresponding free-stream variation can be derived in a similar manner as the single-run uncertainties. Note that the equivalence ratio for each experiment was calculated based on the reservoir conditions for that particular run.

In Fig. 2 we plot a reservoir pressure trace from a typical experiment, together with scaled free-stream Pitot and static pressure traces. Comparing with Fig. 1 of Ref. [18], we see the benefit of

Table 1
Mean facility reservoir (subscript 0) and computed free-stream (subscript ∞) properties from the test condition employed in the present study, together with associated single-run uncertainties.

	Reservoir		Free-stream				
	p_0 (MPa)	h_0 (MJ/kg)	M	p (kPa)	ρ (kg/m^3)	T (K)	u (m/s)
Mean	18.4	3.2	7.36	2.1	0.028	260	2380
±	0.9	0.1	0.02	0.1	0.001	8	50

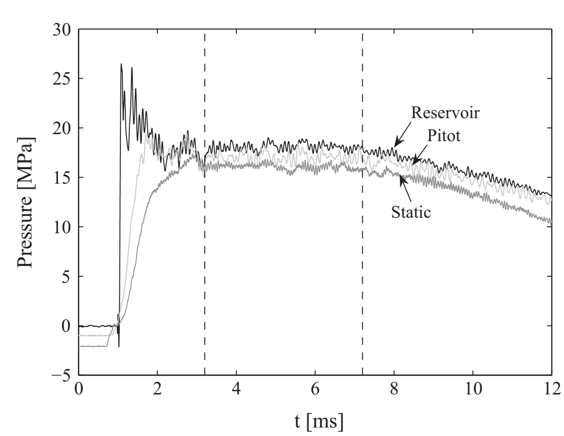

Fig. 2. Typical reservoir and free-stream Pitot and static pressure traces (the latter two scaled and shifted vertically for clarity) from an experiment in the present study. The quasi-steady test time is indicated by the dashed vertical lines.