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Flame propagation and stabilization in dual-mode scramjet combustors: A survey

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ABSTRACT

The dual-mode scramjet combustor is a promising candidate for the combined cycle engine of the hypersonic airplane, and the flame propagation and stabilization process in the dual-mode scramjet combustor has a great impact on its performance improvement. In this survey, the research progress on the flame propagation and stabilization in the dual-mode scramjet combustor is reviewed and summarized, and its main focus is on the flame stabilization mode, especially for the mode transition. The flame stabilization process in the dual-mode scramjet combustor is summarized from three aspects, namely the combustion mode classification, the mode transition and the vitiation effect. The obtained results show that the operational conditions and the geometric parameters both have a great impact on the flame propagation and stabilization process in the dual-mode scramjet combustor, and there exist strong interactions between the geometric parameters, as well as the operational conditions. This is a multiobjective design optimization problem, and the optimal operational conditions, as well as the optimal geometric parameters, should be obtained by the optimization algorithm based on the surrogate model with high fidelity.

1. Background

Recently, the strategic value of the near space has drawn an ever increasing attention of many countries, and the investigation on the near-space aircraft has increased in order to obtain high flight speed and long striking distance. In order to accommodate the severe environment around the near-space aircraft, i.e. nearly 4500 °C on its surface, the heat-resisting ablation material has been employed on the surface of the aircraft [1], and many thermal protection strategies have been proposed and studied in recent years [2], namely the counterflowing jet [3], the forward-facing cavity [4], the aerospike [5], the energy deposition [6] and their combinational configurations [7]. Many countries have spent lots of money on the study of the near-space aircraft, i.e. the USA, Russia, Europe, Korea, Japan, Israel, and others [8]. The key technologies of the near-space aircraft mainly include hypersonic propulsive technique, engine/airframe integration, hypersonic aerodynamics/thermodynamics, structure and material, guidance, navigation and control [9]. For the scramjet combustor, its peak heat flux is about 7–8 MW/m^2, and the largest total temperature is about 2500–3100 K when the vehicle flies with the freestream Mach number being 6.0–8.0. Many thermal protection strategies have been proposed and investigated in order to avoid the burning of the combustor wall in a short time, namely the passive thermal protection scheme using the ablation materials, composite materials et al., the active thermal protection scheme using the low temperature fluid such as kerosene, and the combinational scheme. Wang et al. [10] summarized the research progress of active cooling of endothermic hydrocarbon fueled scramjet engine from five aspects, namely cooling capacity and heat sink measurement, thermal and catalytic cracking, coking suppression, heat transfer characteristics, and injection, mixing, ignition and combustion performance.

As one of the most important techniques in the hypersonic propulsion system, the study on the supersonic combustion has drawn an ever increasing attention, and this is because the problem of fuel injection as well as flame holding is known to play an important role in the flowpath design of the scramjet engine. Curran [11] provided a general review of supersonic combustion ramjet engine technologies in terms of the efforts completed or proceeding in the USA, Russia, France, Germany, Japan, Australia, and other countries. In 2004, the USA tested successfully a scramjet engine propelling a hypersonic vehicle at Mach 6.83 and Mach 9.68, and this is the first-ever example to develop safer and more economic space access vehicles in the future [12,13]. However, its powered flight time is only 11s, and only the cruising condition was tested, namely the expected design condition. The dual-mode

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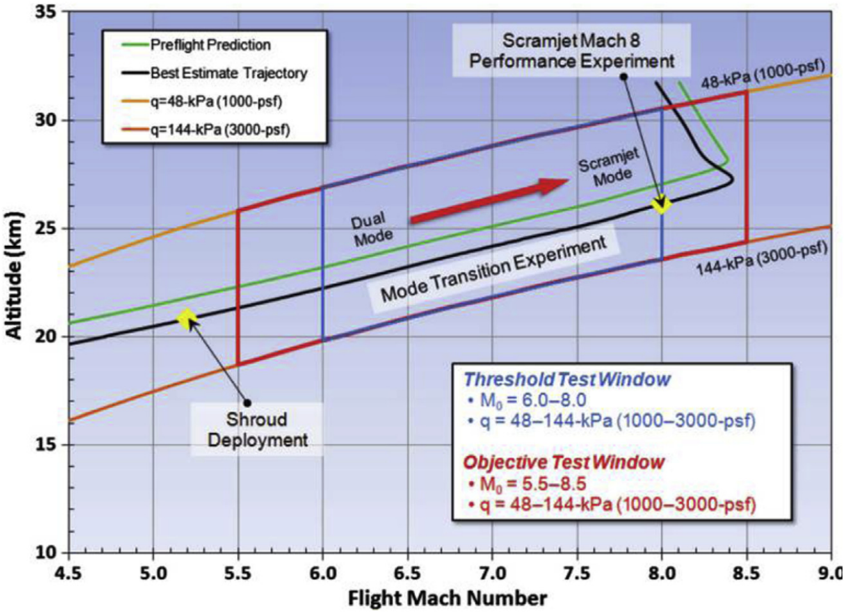

Fig. 1. Test window for the HIFiRE Flight 2 project [20]. Courtesy of Dr. M. R. Gruber.

scramjet engine owns the advantage of producing the positive thrust for a wide range of flight Mach numbers, and it is a promising candidate for the combined cycle propulsion system due to its ability to operate in a mode where the combustion process is largely subsonic or predominately supersonic [14,15]. A large number of dual-mode scramjet experiments are being conducted with the aim of examining the flow processes that occur in the isolator and combustor of a direct-connect scramjet model under the auspices of the National Center for Hypersonic Combined Cycle Flow Propulsion [16]. In order to verify the accelerating performance of the hypersonic vehicle, 4 flight tests of X-51 A propelled by a JP-7 hydrocarbon fuel-cooled scramjet engine were begun in August 2009, and its Mach number range is 4.5–6 [17]. Its largest powered flight time is about 210s, and this is a large improvement since X-43 A was tested successfully in 2004. During the flight, the vehicle is accelerated from 4.8 to 5.1 [18,19]. Additionally, the goals for the HIFiRE Flight 2 project of capturing high-quality flight data from a research scramjet operating through dual-to-scram mode transition up to and beyond Mach 8 were achieved on 1 May 2012 [20], and Fig. 1 depicts the test window for this project. The purpose of this project is to develop and validate fundamental technologies deemed critical to the realization of next generation hypersonic aerospace systems [21]. Kouchi et al. [22] developed a focusing-schlieren system, with a ± 5-mm DOF, to visualize the flowfield in a direct-connect dual-mode scramjet engine. This is the first time successful focusing-schlieren measurements for a dual-mode scramjet engine were performed.

The dual-mode scramjet engine adopts the ramjet mode with the flight Mach number range of three to six and the scramjet mode with higher flight Mach number, in order to offer better performance [23]. The influence of its operation mode on the performance of the vehicle is critical [24]. The ramjet to scramjet transition in a dual-mode combustor typically takes place as the vehicle accelerates, and reverse scramjet to ramjet transitions can only occur in a dual-mode system triggered by the pressure rise from combustion heat addition [25]. In the ramjet mode, the flow in the isolator is characterized either by a normal shock train or an oblique shock train terminating in a normal shock wave, resulting in a fully subsonic flow entering the combustor. The exact nature of the boundary layer in the ramjet mode varies depending on the nature of the shock train, and it is generally a thicker lower-momentum separated flow. In the scramjet mode, there is no precombustion shock wave train, and the flow is purely supersonic with an attached boundary layer [26].

The flame holding device has been generally employed in the dual-mode scramjet combustor in order to form a recirculation zone with longer residence time for fuel/air mixing and combustion, and it includes wall injection [27–34], steps [35], cavities [36–41], struts [42,43], pylons [44–46], backward-facing steps [47,48], ramps [49,50], air throttling [51–53], shock generator [54–58], etc. The cavity as a flameholder has been widely used due to a low total pressure loss [59], and the flame inside the cavity can offer a source of heat and radicals to ignite and stabilize the flame in the main flow [60]. Nakaya et al. [61] evaluated the influence of the fuel vaporization process on the combustion behavior of ethanol in a supersonic combustor with a cavity flame holder experimentally. Due to its potential advantages, the cavity has been utilized in the trapped vortex combustor to stabilize the flame as well, and Zhao et al. [62] reviewed and discussed the cavity flow/aerodynamics, fuel-air injection and mixing, trapped vortex combustion, emission and combustion of alternative fuels, and aeroacoustics properties in the trapped vortex combustor. In 2001, Ben-Yakar and Hanson [41] provided a review on the cavity flame-holders for ignition and flame stabilization in scramjet combustors, and their purpose is to summarize relevant known properties of cavities in supersonic flows. An optimal cavity for supersonic flame holding is required for further investigation, and Kim et al. [63] obtained the same conclusion. Therefore, Huang et al. optimized the geometric configuration of the cavity flameholder [36] and explored the optimized results by means of the variance analysis method [40]. In the optimization process, four geometric parameters were taken into consideration, namely the depth, the length, the height and the swept angle of the cavity. However, only the cold flow field has been optimized, and the flow field with the complex chemical reaction mechanism should be dealt with for deeper understanding of the flow field properties by means of the multiobjective design optimization approach. Wang et al. [64] gave a detailed review on the research progress in the multidisciplinary design optimization (MDO) approach from four primary techniques, namely the design of experiments, the surrogate modeling, the optimization method and the MDO framework. Lawson and Barakos [65] provided a review on the complex flow physics associated with cavity flows and the influence of flow control devices. Further, in 2015, Barnes and Segal [37] summarized the current knowledge of the mechanics of cavity-based flameholding in supersonic flows, and the flame propagation and stabilization is not covered, especially for the mode transition process in the dual-mode scramjet combustor. In this review,