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Unstart phenomena induced by flow choking in scramjet inlet-isolators

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ABSTRACT

A review of recent research outcomes in downstream flow choking-driven unstart is presented. Unstart is a flow phenomenon at the inlet that severely reduces the air mass flow rate through the engine, causing a loss of thrust and considerable transient mechanical loading. Therefore, unstart in a scramjet engine crucially affects the design and the operation range of hypersonic vehicles. Downstream flow choking is known to be one of the major mechanisms inducing inlet unstart, as confirmed by recent scramjet-powered flight tests. The current paper examines recent research progress in identifying flow choking mechanisms that trigger unstart. Three different flow choking mechanisms are discussed: flow blockage, mass addition, and heat release from combustion reactions. Current research outcomes on the characteristic of unstarting flows, such as transient and quasi-steady motions, are reviewed for each flow choking mechanism. The characteristics of unstarted flows are described including Buzzing phenomena and oscillatory motions of unstarted shockwaves. Then, the state-of-the-art methods to predict, detect, and control unstart are presented. The review suggests that further investigations with high-enthalpy ground facilities will aid understanding of heat release-driven unstart.

1. Introduction

1.1. Background

Supersonic combustion ramjets (scramjets) have been developed to power the next generation of hypersonic air-breathing aircraft [1–57]. Like other air-breathing combustion engines, the scramjet demands for a stable oxygen supply from the atmosphere to the combustor being captured at the inlet. Unstart in a scramjet is a flow phenomenon at the inlet that limits the oxygen delivery of the intake air flow to the supersonic combustor [6,8,14,35,41,49,58–93]. Unstart accompanies an unwanted and abrupt oxygen deficit in the combustor and unsteady flow spillage at the inlet, which leads to a loss of both thrust and vehicle control [58,68,73,94]. Consequently, unstart can severely impair the operation of the scramjet. The recent X-51 scramjet-powered hypersonic vehicle flight test, for example, suffered from the inlet unstart [95].

The scramjet flow passage mainly consists of four parts: inlet, isolator, combustor, and exhaust nozzle [96]. The converging inlet compresses and decelerates the incoming supersonic or hypersonic air flow. The isolator, connecting the inlet to the supersonic combustor further decelerates the flow and prevents disturbance propagations from the combustor to the inlet. The combustor supplies thermal energy to the flow via combustion reactions. Finally, the diverging exhaust nozzle accelerates the supersonic flow to generate thrust enabling hypersonic flights [10]. Once the internal flow is choked in the combustor or isolator, the static pressure and temperature quickly rise at the choked location (throat) due to the rapid deceleration of the supersonic internal flow [97–101]. The sudden rises in the pressure and temperature affect the flow in both the upstream and downstream regions. The rapid pressure rise at the choked throat increases the pressure in the subsonic portion (e.g., subsonic regions of boundary layers, subsonic corner flow areas, separated boundary layer regions) of the upstream region via the reverse propagation of sonic pressure waves [75,102,103]. The increased pressure extends the subsonic portion, and under a certain range of conditions, the virtual area of the choked throat decreases. The inlet eventually unstarts when the choked throat reaches the critical condition causing unsteady flow spillage [73,75,78–81,102,104,105]. Conversely, the flow is un-choked at a downstream location. Thus, the sonic point reappears due to the large pressure difference between the choked flow and the atmosphere at a typical altitude for hypersonic flights (see Fig. 1).

The conditions causing unstart can be formulated with i) incoming air flow conditions such as freestream Mach number (*Ma*), pressure, temperature, and turbulence properties, ii) geometric (design) parameters of the inlet and flow passages such as inlet contraction ratio (CR), leading

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Nomenclatures

Ma or M	Mach number
CR	contraction ratio
A	flow area (m^2)
γ	specific heat ratio
TR	throttling ratio
f	friction coefficient
D	hydraulic diameter (m)
F_A	area change coefficient
F_f	friction influence coefficient
V	local freestream speed (m/s)
V_i	jet injection speed (m/s)
α_i	jet injection angle
a_s	speed of sound (m/s)
Φ	equivalence ratio
f_n	resonance acoustic frequency (Hz)
$\bar{a}$	*mean speed of the sound* (m/s)
$\overline{M}$	mean *Ma* in the channel
L	characteristic length of the channel

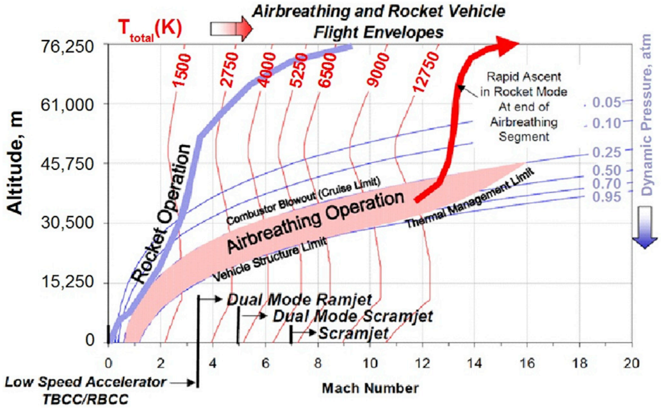

Fig. 1. Air-breathing hypersonic vehicle flight trajectory (altitude and speed) and operational limits [96].

edge angle, and isolator length and iii) downstream pressure build-up from combustion heat release, fuel mass injection, and shockwave/boundary layer-induced deceleration/separation of the internal flow [66].

The i) freestream flow conditions and the ii) geometric parameters passively govern the starting/unstarting criterion; i) and ii) are invariable in steady cruise flights and predetermined by the designated flight trajectory and the corresponding vehicle design. There have been numerous studies delineating the freestream flow conditions and the geometric parameters to define an unstart boundary [61,104,106–109]. In particular, the freestream *Ma* and the inlet CR have been most frequently used to describe the unstart boundary [36,53,107,110–113]. For example, the Kantrowitz limit [114] determines the critical inlet CR causing inlet unstart as a function of freestream (incoming air flow) *Ma* (Eq. (1)):

$$CR_{Kantrowitz}=\left(\frac{A_{inlet}}{A_{throat}}\right)_{Kantrowitz}$$
$$=\frac{1}{M^2}\left[\frac{(\gamma+1)M^2}{(\gamma-1)M^2+2}\right]^{\frac{\gamma}{\gamma-1}}\left[\frac{\gamma+1}{2\gamma M^2-(\gamma-1)}\right]^{\frac{1}{\gamma-1}}\left[\frac{1+\gamma-\frac{1}{2M}^{2}}{\gamma+\frac{1}{2}}\right]^{\frac{\gamma+1}{2(\gamma-1)}} \quad (1)$$

where A_{inlet}, A_{throat}, M, and γ are the inlet area, throat area, freestream *Ma*, and the ratio of specific heats, respectively. When the inlet CR of an axisymmetric scramjet vehicle exceeds the critical CR defined in Eq. (1), excessive compression in the inlet can potentially induce the inlet unstart. Nevertheless, determining a universal critical CR at a given freestream *Ma* as an unstart boundary, e.g., simply a function of only freestream *Ma* as in the Kantrowitz limit, is not practically feasible. For example, in cases with non-axisymmetric 3D inlets, the inlet CR cannot solely define a starting/unstarting criterion [57,115,116]. This is because the criterion depends not only on the inlet CR but also on the geometry of the inlet and the isolator as a whole (Fig. 2). Fig. 2 represents the contraction ratio limits for inlet starting/unstarting, Kantrowitz, isentropic, and empirical limits. As seen in the figure, the Kantrowitz limit alone cannot represent a starting/unstarting criterion. The 3D inlet geometry along the flow path controls the compression process that affects the resulting stagnation pressure loss while the flow contracts through the inlet. The inlet geometry also determines whether the strong incident shockwaves from the leading edges (lips) enter the isolator and the strength of these shocks. Once the incident shockwave enters the isolator, sequential reflections of the shockwave along the flow passage will further compress the flow [43,57,107,117–119]. The flow will be choked when the compression through the inlet and the isolator is excessive (Fig. 2). Furthermore, the shape of the cross-section in the inlet and the isolator can also affect the unstart boundary [45,51,107,120–128]. The shape will determine the structure, interaction, and strength of the incident and the reflected shockwaves, as well as the development of the boundary layers on the internal surfaces, corner flows, and their interactions with shockwaves. These important internal flow features significantly influence the formation and distribution of subsonic flow area in the internal flow passages that will potentially deliver pressure waves from the downstream high-pressure region toward the inlet when the unstart process is triggered [75,102,103].

The internal flow choking and unstart are also caused by the downstream pressure build-up due to flow deceleration [129], fuel mass addition [104], and combustion heat release [109]. The pressure rises from fuel mass injection and accompanying combustion heat release are typically much higher than that from the flow deceleration depending largely on the geometry of flow passages [109]. Therefore, fuel mass injection rate and combustion heat release have been regarded as the crucial scramjet operation conditions that can actively trigger or prevent the internal flow choking and unstart [10,98–100,109]. Fuel mass injection and the following combustion heat release are closely correlated, i.e., the combustion heat release will monotonically increase with the fuel injection rate presuming operations in overall fuel-lean conditions. The correlation would, however, vary with the combustor geometry, fuel injection strategy, injection location, and injection direction [128,130–138]. Ultimately, the scramjet combustor would be designed to maximize the combustion efficiency (ratio of burnt fuel to the injected fuel) and to minimize the simultaneous and conflicting stagnation pressure loss that occurs in practice [56,57,136,137,139–141]. Hence, there is no generic or representative correlation between the fuel mass injection rate and the combustion heat release. Therefore, it is practically unavoidable to separate the two, mass and heat additions, in formulating the unstart conditions.

1.2. *Scope of the review*

The current paper aims to provide an overview of flow choking-driven unstart in scramjets and the resulting flow phenomena. As addressed above, the causes of unstart are typically categorized by three factors, freestream conditions, an inlet-isolator geometry, and downstream flow choking. Chang et al. [107] recently outlined the research progress on these three unstart mechanisms. Freestream condition- and geometry-driven unstart phenomena primarily concern the flow at the lip of the scramjet inlet. Consequently, the phenomena are relatively simpler than those induced by downstream flow choking because unstart driven by flow choking involves the flow phenomena of the entire internal flow