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Effect of cowl shock on restart characteristics of simple ramp type hypersonic inlets with thin boundary layers

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ABSTRACT

The effect of cowl angle on the restart characteristics of simple ramp type hypersonic inlets was experimentally investigated in shock tunnel equipped with schlieren imagery and static pressure measurement. The cowl shock strength is found to be a key factor that determines the inlet restart and makes the restart contraction ratios significantly deviate from the Kantrowitz criterion. Stronger cowl shock tends to degrade the inlet restart capability by causing larger separation bubble and higher pressure loss during the restarting process. In particular, a sensitive range of the cowl angles, within which the restart contraction ratio decreases rapidly, was identified. A design concept of multiple noncoalesced cowl shocks was thus proposed and proven to significantly improve the inlet restart capability.

1. Introduction

Hypersonic inlets use a combination of external and internal compression, which adds complexity in the inlet starting, especially for the fixed-geometry configurations. The inlet has the risk of becoming unstarted at low flight Mach number, or large angle of attack, or high back pressure rising in the combustor [1,2]. Mahapatra and Jagadeesh [3] and Chang et al. [4] even found so-called local unstart at high Mach number. The inlet restart capability is therefore crucial for efficient operations of hypersonic aircraft. Numerous studies have been conducted to investigate the inlet restart (or self-starting) characteristics.

In the early studies [5,6], Kantrowitz proposed a theoretical model for supersonic inlet restart based on the assumptions that a normal shock wave stands at the cowl lip station and the quasi-steady, one-dimensional, isentropic internal flow has a sonic condition at the inlet throat. The maximum allowable internal contraction ratio was consequently derived as a function of the inflow Mach number. Mölder et al. [7], Najafiyazdi et al. [8] and Veillard et al. [9] further studied the limiting contractions for restarting scramjet inlets with overboard spillage or wall perforations based on the Kantrowitz theory. Although the theory provides a basic criterion for inlet design, the hypersonic inlet starting process, involving complex shock patterns accompanied with a large scale boundary layer separation, is significantly different from the simplified assumption of swallowing a normal shock. A number of experiments have verified that the inlet can restart at internal contraction ratios beyond the Kantrowitz limit [10,11], and a significant scatter in the restart contraction ratios has been observed [10,12]. These indicate that the Kantrowitz theory is not applicable to hypersonic inlets because of the oversimplified assumptions mentioned above. The restart problem should be attributed, at least in part, to the shock–boundary layer interaction in the region of the cowl leading-edge station, and it has strong relations with other factors besides Mach number.

Taking the actual viscous flow into account, Goldberg and Hefner [13,14] studied the restart capability of a simplified two-dimensional inlet with thick boundary layers relative to the inlet height at Mach 6.0. The dependence of restart contraction ratios on the inlet geometries, the relative boundary layer thickness, and the wall-to-freestream temperature ratio were preliminarily surveyed. The inlet cowl angle is found to have a favorable effect on the inlet restart, which contradicts with our conventional understanding. In fact, it is noted that the results were simultaneously coupled with the variation of relative thickness of boundary layers.

McGregor et al. [15] investigated the starting process for planar inlets in a gun tunnel at Mach 8.3 for various contraction ratios, Reynolds numbers and initial tunnel pressures. The inlet starting is promoted by lowering the pre-start back pressure in the tunnel, by decreasing the contraction area ratio, and by decreasing the cowl angle.

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Van Wie et al. [16] further investigated the unstart/restart characteristics of a small-scale rectangular inlet at Mach 3.0 and observed two types of unstart/restart behavior, which are classified as “hard” or “soft” based on the occurrence of hysteresis. Although a crude boundary between the soft and hard modes was drawn in the parameter space of cowl length and cowl height, their transition criterion needs to be further clarified. It is likely to be related to the cowl angle because the restart contraction ratio corresponds to a specific cowl angle at given cowl length and height.

Flock and Gülhan [17] experimentally studied the restart behavior of a three-dimensional scramjet inlet and found that exchanging the V-shaped cowl with a straight-cowl geometry improved inlet starting with the additional mass spillage. In recent years, increasing attentions have been paid to developing various methods of promoting the inlet starting. Chang et al. [18,19] studied the effects of bleeding on unstart/restart characteristics of hypersonic inlets and found the bleeding can reduce the starting Mach number. Tahir and Mölder [20] and Ogawa et al. [21] proposed a method by taking advantage of highly unsteady effect. Variable geometry techniques were also investigated extensively for inlet starting [22,23].

In spite of aforementioned advances in understanding hypersonic inlet restart, the roles of cowl shock have not been adequately clarified and a general design rule for improving the inlet restart has not been established. Specifically, cowl shock was found to have some effects on the inlet restart, but to our knowledge, details of how it affects the inlet restart are not available, particularly when decoupled from other factors. The present study was motivated to elucidate the influence of the cowl shock on the restart characteristics. Simple ramp type inlet models were designed for facilitating the focus on the cowl shock effects. Thin boundary layers were considered in the present study because they occupy less than one fourth of the cowl lip height in the hypersonic inlets.

2. Experimental setup

2.1. Wind tunnel and test conditions

The present experiments were conducted in the GJF shock tunnel of Institute of Mechanics, Chinese Academy of Sciences. The shock tunnel, operating at equilibrium interface condition, is equipped with an 11.2 m-long driver section and a 22 m-long driven section filled with compressed air, followed by an axisymmetric nozzle, test section and vacuum tank, as shown in Fig. 1. The test chamber is fully closed with two embedded glass windows (350 mm in diameter) for optical access. In the present experiments, the nozzle Mach number M_∞ was 4.0, the static pressure p_∞ is 9.0 kPa, the total temperature T_0 is 430 K, and the unit Reynolds number $\mathrm{Re}_{\infty,m}$ is 3.58×10^7/m. A typical test duration is about 25 ms, as shown in Fig. 2, in which $t = 0$ indicates the time instant when the pressure sampling was triggered by the pressure transducer in the upstream of the nozzle.

2.2. Technique for inlet restart test

To examine the hypersonic inlet restart characteristics within the short duration of the shock tunnel, a newly proposed test method [24], which has been validated against the experimental data from blow down tunnels, was adopted in the present study, as shown in Fig. 3. A Terylene diaphragm is placed at the inlet exit with a coherent electric resistance wire on its leeward insulated from the shock tunnel and inlet model. At the beginning, the inlet is choked into big buzz due to the obstruction of the diaphragm. Concurrently, the voltage signal from the total pressure transducer triggers the delay-time signal generator, which in turn generates a pulse voltage signal after a specified delay of 40 ms to actuate the high-voltage igniter. The diaphragm is subsequently ruptured within a few milliseconds due to the heating of the electric resistance wire. It is noted that the delay time is specified so that the diaphragm rupture occurs within the effective shock tunnel duration after the establishment of periodic unstarted flow in the inlet. Similar to that of conventional wind tunnels, the inlet restarting process can be investigated to check its restart capability after the disappearance of the choke.

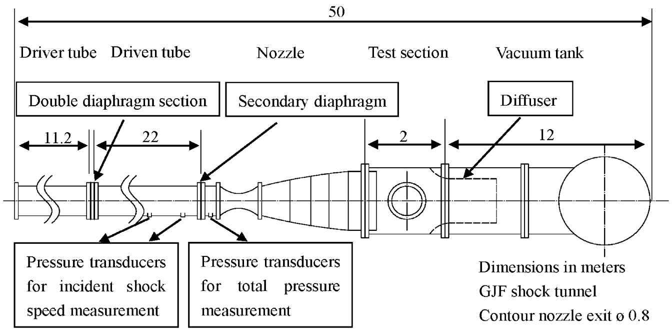

Fig. 1. Sketch of the GJF shock tunnel (unit: m).

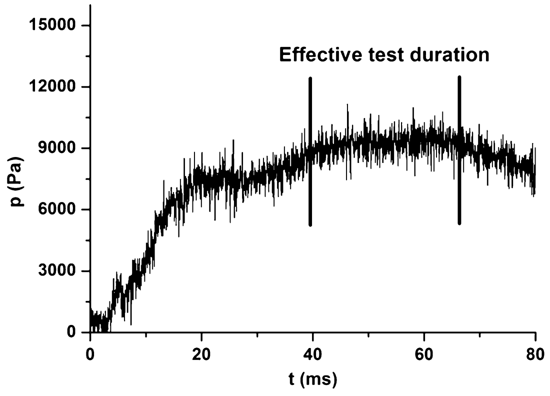

Fig. 2. A typical static pressure–time history at the nozzle exit.

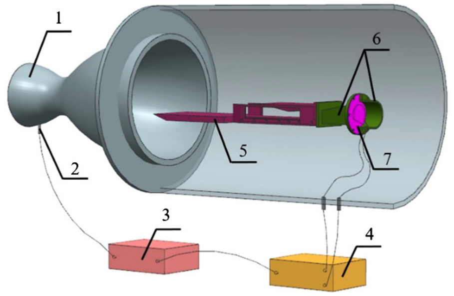

Fig. 3. Schematic of the experimental devices for inlet restart in shock tunnel. 1. Shock tunnel nozzle, 2. Pressure probe, 3. Delay time signal generator, 4. Electrical igniter, 5. Inlet model, 6. Device for diaphragm installation, 7. Terylene diaphragm.

2.3. Simplified inlet model

As with Refs. [10,13,14], a simplified inlet model, as shown in Fig. 4(a), was tested in the present investigation to gain an in-depth understanding, which would be applicable to realistic hypersonic inlets. The model has a constant span width of 80 mm, five different wedge angles $\alpha = 7°$, $8°$, $9°$, $11°$ and $15°$ for varying the cowl shock strength, and two different cowl lip heights H are designed as 30 mm and 40 mm. The boundary layer thickness at the cowl lip station is directly related to the bottom plate length in the upstream of the cowl lip, which is designed as $L = 200$ mm,