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Investigation of hypersonic inlet pulse-starting characteristics at high Mach number

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ABSTRACT

An unsteady viscous numerical simulation is performed to study the hypersonic inlet pulse-starting in a shock tunnel under the condition of inflow Mach number higher than the design value with a simplified nozzle startup wave system. A local unstart of hypersonic inlet is obtained with the initial backpressure and temperature of test section equal to the hypersonic freestream static pressure and static temperature, respectively. During the hypersonic inlet pulse-starting process, the nozzle startup wave system (including the primary shock, contact discontinuity and secondary shock) propagates downstream and interacts with the hypersonic inlet, the secondary shock induces boundary layer separation on the compression ramp. A low velocity flow induced by the separation bubble enters into the internal duct with the passage of time. It thickens the boundary layer and then the cowl shock induces a large separation bubble on the compression side. The shock induced by the large separation bubble impinges on the cowl and induces a small separation bubble, which moves upstream and induces the reflection of the external compression shock at the cowl transiting from regular reflection to Mach reflection. Mach reflection results in the shock propagating forward to cause a shock detachment at the cowl lip. The hypersonic inlet is not fully started and this phenomenon is referred to as "local unstart of inlet". Moreover, it is found that the hypersonic inlet starts with lower initial backpressure or higher initial temperature of test section, and the hypersonic inlet unstarts with higher initial backpressure. The effect mechanism is analyzed with the help of numerical simulations and unsteady one-dimensional shock theory. As there are three operation modes of hypersonic inlet at high Mach number: start, local unstart and unstart. The results of the hypersonic inlet pulse-starting in a shock tunnel should be carefully treated.

1. Introduction

As the main compression component of a hypersonic propulsion system, the inlet affects the performance of scramjet greatly. The starting problem is the most critical item in the design of the hypersonic inlet. If an inlet is not started, the mass capture will be greatly reduced, and the spillage drag will be excessive. For hypersonic air-breathing engines, inlet unstart will cause a large drop of both engine thrust and specific impulse, and it may cause a catastrophic damage during hypersonic flight [1].

Over the past few decades, the subject of hypersonic inlet start/unstart have been studied extensively [2–22]. Many experimental investigations are carried out in ground test facilities, which are capable of simulating hypervelocity flow. The pulse facility is one of the most popular types of facilities as it offers many advantages. The pulse facility is capable of producing high total pressure and total enthalpy flows required at the hypersonic flight conditions, and the cost of construction and operation are lower than in other types of facilities. It has been shown that the inlet starts easier and faster with lower backpressure of test section in pulse facilities [3,22]. The inlet with larger internal contraction ratio (ICR), which can not be started in general facilities, could be started in pulse facilities [3,23], because of the unsteady effects in flow establishment of the facility [24] which have strong capability of helping inlet to start. The mechanism is not clear yet. Atkins [25] theoretically studied the nozzle startup wave structure in a shock tunnel with the help of inviscid simulation and then numerically studied the mechanism of inlet pulse-starting with the simplified nozzle startup wave system. Wang et al. [26] numerically studied the unsteady starting of a hypersonic inlet with the

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Nomenclature

c	speed of sound
D	diameter of the parabolic reflector
M	Mach number
p	pressure or pressure ratio
t	time
V	velocity
X	X-axis coordinate
Y	Y-axis coordinate
γ	specific heat ratio

Subscripts

cr	critical condition
ps	primary shock
s	moving shock
ss	secondary shock
0	freestream
1	zone downstream of the primary shock
2	zone upstream of the primary shock
3	zone upstream of secondary shock
4	zone downstream of secondary shock

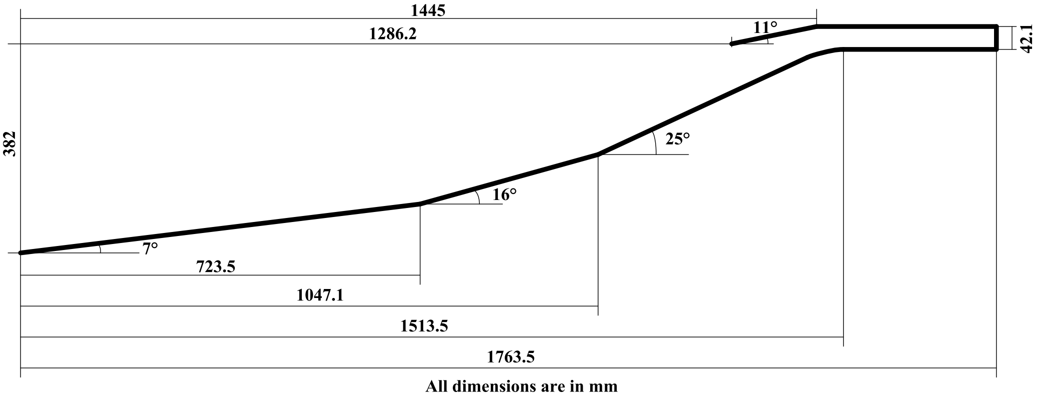

Fig. 1. Simulation hypersonic inlet model.

simplified nozzle startup wave system same as Atkins. However, these works mainly focus on inlet pulse-starting at Mach number lower than or equal to the design value.

Hypersonic inlet works in a wide range of Mach numbers and the design Mach number is generally a middle value. So, it may work at a Mach number higher than the design value [27, 28]. When hypersonic inlet works at a high Mach number, the forebody shock wave impinges on the cowl at a position downstream of the lip and reflects. The reflection of shock wave result in two types of wave configurations: regular reflection (RR) and Mach reflection (MR) [29]. The hypersonic inlet is started with a regular reflection of the forebody shock wave at the cowl. Whereas a Mach reflection will result in the shock propagating forwards to cause a shock detachment at the cowl lip, which is called “local unstart of inlet” by Jiao et al. [30]. Mahapatra and Jagadeesh [31] experimentally observed the local unstart of a two-dimensional simplified inlet model in a hypersonic shock tunnel. And they studied the effect of cowl length on the pulse-starting characteristics of hypersonic inlet at high Mach number. However, the evolvement of local unstart of a full size hypersonic inlet and the pulse-starting characteristic of hypersonic inlet with fixed geometry at high Mach number were not carefully considered.

This paper focuses on the pulse-starting of a full size hypersonic inlet with fixed geometry at high Mach number. Unsteady viscous numerical simulations are performed with a simplified nozzle startup wave system. The evolvement of local unstart of hypersonic inlet is studied. And the effects of the initial back-pressure and temperature of test section on the hypersonic inlet pulse-starting at high Mach number are analyzed with the help of numerical simulations and unsteady one-dimensional shock theory.

2. Inlet model and numerical method

2.1. Inlet model

The simulation model in this paper is a 2-D hypersonic inlet. The external compression of the inlet is achieved by three ramps inclined by 7 deg, 16 deg and 25 deg to the freestream flow direction, respectively. The fore part of the cowl uses a single ramp inclined by 11 deg to the horizontal line. The detailed geometry information is shown in Fig. 1. The numerical investigation is performed at an inflow Mach number of 7.0 and the corresponding static pressure and static temperature are specified as 1845 Pa and 223.7 K, respectively. The external compression shock waves impinge on the cowl under the condition.

2.2. Numerical method

The two-dimensional compressible Reynolds-averaged Navier–Stokes (RANS) equations are adopted as the governing equations, and the shear stress transport (SST) k–ω two-equation model is employed as the turbulent model because it leads higher accuracy of the simulation of the whole flowfield by treating the high-speed flow in the main stream with the k-epsilon model and treating the low velocity flow in the near wall region with the standard k-omega model. An implicit algorithm with second-order spatial accuracy and dual time-stepping is used for the computation of transient flow field. The global time step is set as 1e−7 s, which is much lower than the flow timescale of the nozzle startup wave system propagation. The transient flow field is converged at every global time step. The fluid is modeled as a single-specie, thermally perfect air. The piecewise-polynomial method is selected to compute specific heat ratio while viscosity is solved using Sutherland’s formula. The advection upstream splitting method (AUSM)