Aerospace Science and Technology 50 (2016) 25–30

Contents lists available at ScienceDirect

Aerospace Science and Technology

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Visualization of stagnation point inside the closed wake of a 20%-truncated plug nozzle at starting process

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ARTICLE INFO

Article history:
Received 2 July 2015
Received in revised form 25 October 2015
Accepted 7 December 2015
Available online 14 December 2015

Keywords:
Plug nozzle
Background-oriented schlieren
Starting process
Shock tube

ABSTRACT

Flow visualization using the background-oriented schlieren (BOS) technique was used to investigate the characteristics of the stagnation point shift near the nozzle base of a 20%-truncated planar plug nozzle designed for a Mach number of 2.87 at the nozzle exit. The nozzle pressure ratios ranged from 7 to 120. A shock tube with a cross-section of 3 × 4 cm is used as a high-pressure gas reservoir. The obtained images were compared with the Navier–Stokes numerical solution obtained with the weighted averaged flux method. First, to confirm the establishment of steady flow, the starting process inside the nozzle was visualized using shadowgraph. Next, BOS images were used to determine the location of the stagnation point inside the closed wake. The images revealed that the distance of the stagnation point from the base surface was 1.3 times the throat width after the closed wake mode was established.

1. Introduction

Conventional rocket engines, the bell type (Fig. 1a), have primarily been used for the propulsion of launch and space vehicles. In the future, advanced rocket propulsion systems will require exhaust nozzles that perform efficiently over a wide range of ambient operating conditions. Furthermore, these exhaust nozzles should be short, lightweight, and relatively easy to cool. Analyses and tests have shown that a group of nozzles referred to as altitude compensating nozzles satisfy these requirements. As shown in Fig. 1b and c, expansion-deflection and plug nozzles are included in this group. Altitude compensation in these nozzles is obtained by the flow of the combustion products in the supersonic range. Unlike the bell nozzle, in which the entire flow is contained within a fixed contour, the flow in a plug nozzle is guided along the plug only. The outer shroud ends shortly after the nozzle throat and forces the flow to establish its own external contour, which must be in pressure balance with the ambient conditions.

The flow field produced by circular plug nozzles has been studied for several decades [1–3]. By adjusting the effective nozzle area ratio, the altitude compensation feature gives a plug nozzle a significant performance advantage over a bell nozzle. Its thrust efficiency at low altitudes can be significantly higher than that of a bell nozzle. This low-altitude performance gain produces a higher average specific impulse during ascent into the space.

The second feature, which is better vehicle base utilization, derives its attractiveness from three related areas. First, the vehicle base area produces a drag. Use of a plug nozzle reduces the size of this drag-producing base area. Second, because almost the entire vehicle base can be used as the nozzle exit area, nozzle area ratios up to 150:1 are realistic. This large nozzle area ratio allows a plug nozzle to have higher thrust performance in a vacuum. Third, the engine thrust is transmitted to the vehicle as a large source load as opposed to a point source load in the case of a bell nozzle. This distributed thrust load offers the possibility to reduce the thrust structure weight.

On the other hand, the considerable weight of a plug nozzle is of serious concern and needs to be addressed. Reducing the length of the nozzle ramp is a solution. This could also be advantageous for the cooling effort of the nozzle. Therefore, truncated plug nozzles (Fig. 1d) are now frequently being incorporated in launch and space vehicle designs.

As shown in Fig. 2, depending on the chamber to ambient pressure ratio, two significant nozzle operation modes can be identified. At a low pressure ratio, the separated base flow region is open and is sensitive to ambient conditions through the trailing wake corridor (Fig. 2a). For a high pressure ratio, the base flow field is closed, preventing any influence of the ambient environment (Fig. 2b). Experiments have shown that in the open-wake condition, the base pressure varies in accordance with the ambient pressure. After the wake closes, the base pressure remains

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http://dx.doi.org/10.1016/j.ast.2015.12.013
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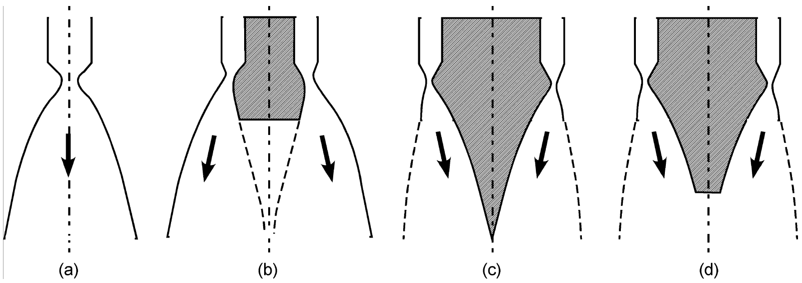

Fig. 1. Type of nozzle.

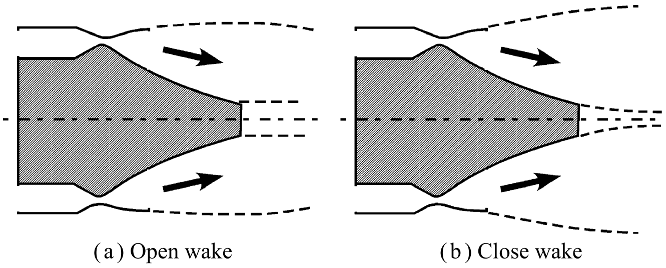

Fig. 2. Operation modes of the truncated plug nozzle.

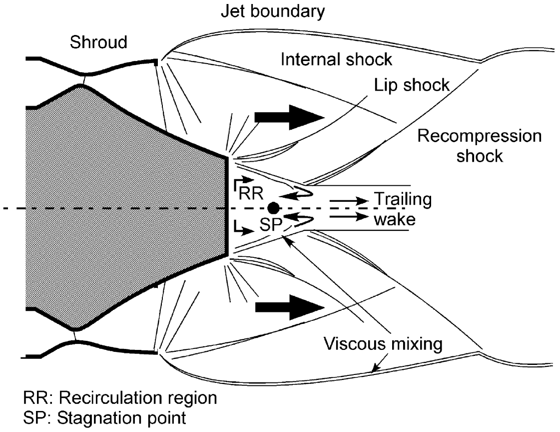

Fig. 3. Typical flow structure of the closed wake.

constant. The typical and detailed structure of the closed wake is shown in Fig. 2b [4].

Interestingly, several studies on the numerical analysis of the thrust of truncated plug nozzles have reported that a truncated plug nozzle can deliver almost the same thrust as a full-length plug nozzle. This is because a relatively high-pressure region appears near the nozzle base owing to jet collisions. Ito et al. [5–7] have reported that the pressure recovery generated by the interference of flow at the base region acts as the stagnation pressure for generating thin supersonic flow directed from the pressure recovery point toward the nozzle base wall (see Fig. 3). To the best of the authors' knowledge, trust compensation effects have not yet been evaluated using experimental methods with flow visualization.

2. Experimental method

2.1. Planar truncated plug nozzle

Fig. 4 shows the schematic of the planar truncated plug nozzle examined here. The nozzle was designed to operate at a pressure ratio of 30 and an exit Mach number of 2.86. The shape of the nozzle ramp was determined by the characteristic method (Lee's method) [8]. The design assumed that a series of centered isentropic expansion waves occur at the cowl lip of the nozzle. The area ratio of the nozzle is 3.71 at the end of the ramp corresponding to the Mach number of 2.86. After determining the entire shape of the nozzle, the ramp was truncated by 20% of its full length.

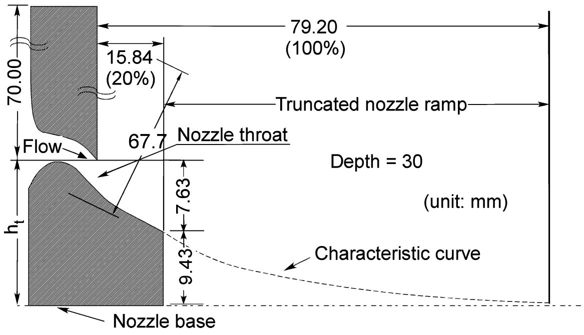

Fig. 4. Schematic of the planar 20%-truncated plug nozzle.

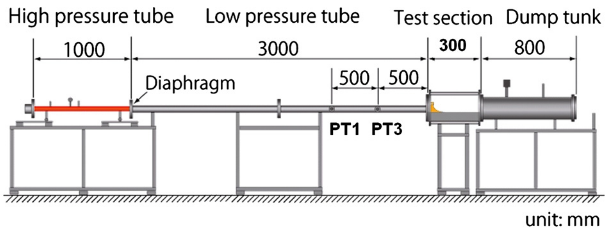

Fig. 5. 3 × 4 Single diaphragm shock tube (3 × 4 SDST).

2.2. Shock tube

Fig. 5 shows the shock tube employed as a stagnation pressure generator for nozzle operation. At the end wall of the low-pressure tube, high-pressure gas appears behind the reflected shock wave propagating toward the high-pressure tube. Thus, the shock tube, which is named 3 × 4 SDST, can function as a stagnation generator. The shock tube consists of a high-pressure chamber of diameter 50 mm and length 1000 mm, a 3000-mm long low-pressure chamber with a 40 mm × 30 mm cross-section, a 300-mm long visualization chamber, and a dump tank with an inner diameter of 200 mm and a length of 800 mm. The test gas was dry air at 10 kPa, and the driving gases were dry air at 200 kPa–1.5 MPa and helium at 1.8 MPa. Mylar films (polyethylene terephthalate) of 75–250 μm were used as diaphragms separating the high-pressure driving gases from the low-pressure test gas. The shock speed was measured by two pressure transducers (PCB model 482C05) placed 500 mm apart in front of the test section. The shock Mach number realized varied from 1.80 to 4.05, i.e., the pressure ratio of the stagnation pressure P_{01} to the nozzle exit pressure P_a varied from 9.5 to 55.