Color Schlieren Imaging of High-Pressure Overexpanded Planar Nozzle Flow using a Simple, Low-Cost Test Apparatus

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Abstract Complex flow features within rocket nozzles can exert significant influence on both the dynamics and safety of rockets during flight. Specifically, under over-expanded flow conditions, during, low altitude flight, random, often large side loads can appear within nozzles. While significant research has focused on this classical problem, due to the high nozzle pressure ratios (NPR) extant across rocket nozzles, most experimental work: (1) has focused on measuring wall pressure distributions under conditions when side loads appear, (2) has been carried out in large government or industrial test facilities, and (3) has only provided limited, though crucially important, visualization data. This short paper describes the construction and operation of a very simple, low cost test apparatus that allows imaging of flow features within planar nozzles, under the high NPR conditions characteristic of medium-to-large rockets. A representative color Schlieren image of flow shock structure obtained within the test apparatus is also presented and briefly described.

Keywords: Rocket Nozzle, Schlieren, Side Load, Experimental, High Pressure

1. Introduction

Problems related to side loading of rocket nozzles have long plagued rocket designers. Over the last 50 years, due to a number of structural and catastrophic failures, including that of the Japanese H-II in 1999 (Sekita et al. 2001), the problem has received significant research attention (Nasuti and Onofri 2009). Most experimental studies have focused on measuring wall pressure distributions under conditions where side loading occurs; see, e.g., (Tomita et al. 2009; Foster and Cowles 1949). A large number of numerical studies have focused on the fluid dynamic processes that underlie side loading (Gross and Weiland 2004; Chen et al. 1994; Bocaletto and Lequette 2005).

A central difficulty that has limited research in this area concerns the dearth of visualization data on flow features and processes that accompany side load generation. Although a number of visualization studies have been reported on separation and side loading in planar nozzles, (Papamoschou et al. 2009), these are largely limited to flows in which the nozzle pressure ratio

(NPR) lies well below the range characteristic of medium and large rockets. (The NPR is the ratio of combustion chamber pressure to ambient pressure.) Due to significant differences in, e.g., shock strength, shock angle, and separation line motion under low and high NPR conditions, it is crucial that visualization data be obtained under NPRs of appropriate magnitude.

Historically, and unfortunately, such measurements have required use of expensive and often difficult-to-access experimental facilities. The purpose of this Short Paper is to describe a *simple, low-cost* approach for designing and building high NPR nozzle test stands, suitable for essentially any optical diagnostic and for investigation of a wide range of fundamental problems in high speed nozzle flow. The test stand is demonstrated via application of color Schlieren to imaging a side-load inducing shock structure within a planar nozzle, operating under high Mach number, high NPR flow conditions.

2. Experimental Apparatus

The nozzle test apparatus is designed to meet the following experimental requirements: i) It must allow testing over the range of NPR's, approximately, 40-150, representative of those used in medium-to-large-scale rockets. ii) The apparatus must allow ready optical access. iii) The system design must be safe and inexpensive to construct and operate.

An image of the experimental nozzle is shown in Fig. 1. Under this range of NPR's, a typical apparatus must provide near-exit nozzle pressures that are smaller than ambient. For simplicity, a low pressure exit (vacuum) chamber is not used; rather, the nozzle flow is allowed to exit directly to ambient. In order to achieve NPR's on the order of 150, while again minimizing construction and operating costs, a small, high pressure tank is used. Maximum experimental pressures are 164 MPa (2400psi) while all components are rated to over 200 MPa.

To allow optical access, a standard planar nozzle was machined from steel, with high strength tempered glass panes bolted and sealed to the steel nozzle structure. We carried out maximum pressure trials away from human operators.

The key feature which allows low-cost operation derives from the short experimental run times. The time interval over which the maximum pressure, set during charging of the tank, remains nominally fixed was nominally about 0.10 s and complete runs last about 0.93 sec. Although seemingly short, this time span is in fact long compared to the time scale required for pressure driven ambient air to flow into the nozzle (due to the over-expanded condition at the exit) and to turn on itself to from a shock-inducing compression corner. Thus, flow features and structure remain in a quasi-steady state during the imaging operation.

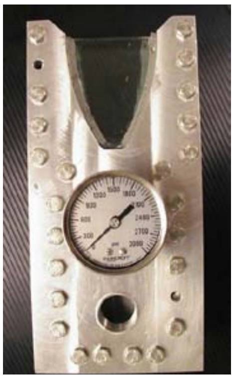

Fig 1. Front view of Experimental Planar Nozzle

As another cost-saving measure, a simple high pressure ball valve is chosen for controlling flow from the pressurized tank to the nozzle. Importantly, these valves respond rapidly when manually actuated; there is no detectable ramp-up in nozzle entrance pressure once the valve is opened. For safety purposes, the tank is connected to the nozzle entrance using hydraulic lines rated for 340 MPa. In all experiments, the tank is charged with Argon gas to 150 MPa.

The nozzle profile is that of a thrust optimized profile (Sutton and Biblarz 2010). As a means of directly measuring near-wall Mach number distribution, striations were purposely added to the walls to form weak oblique shock waves. The near wall Mach number distribution in turn, will be used in studies of shock induced boundary layer separation and side-loading (Tomita et al. 2009).

For these imaging studies, the color Schlieren method has been chosen and experiments are recorded on a standard high definition digital camcorder running 30 frames per second. Due the combination of relatively slow frame rate and short experimental run time (0.1 s), only three images, again obtained at the pre-run charge pressure are typically obtained.

3. Experimental Results and Discussion

As a demonstration of the system’s imaging performance, we present in Fig. 2a and 2b representative images of the shock structure (having nominal maximum Mach numbers of 4.4 and 2.0, respectively). In these respective images, the upstream pressures are approximately 150 MPa and 75MPa. Typically, the direction of the density gradient is indicated by the color; however, the expansion fans forming around the nozzle throat have such a high gradient that they appear black. Another observation is the large number of weak oblique shocks rolling off the upper and lower walls. These are formed by striations on the nozzle walls and coalesce at the internal shock. The angle of these shocks from the wall provides an indication of the local Mach number.

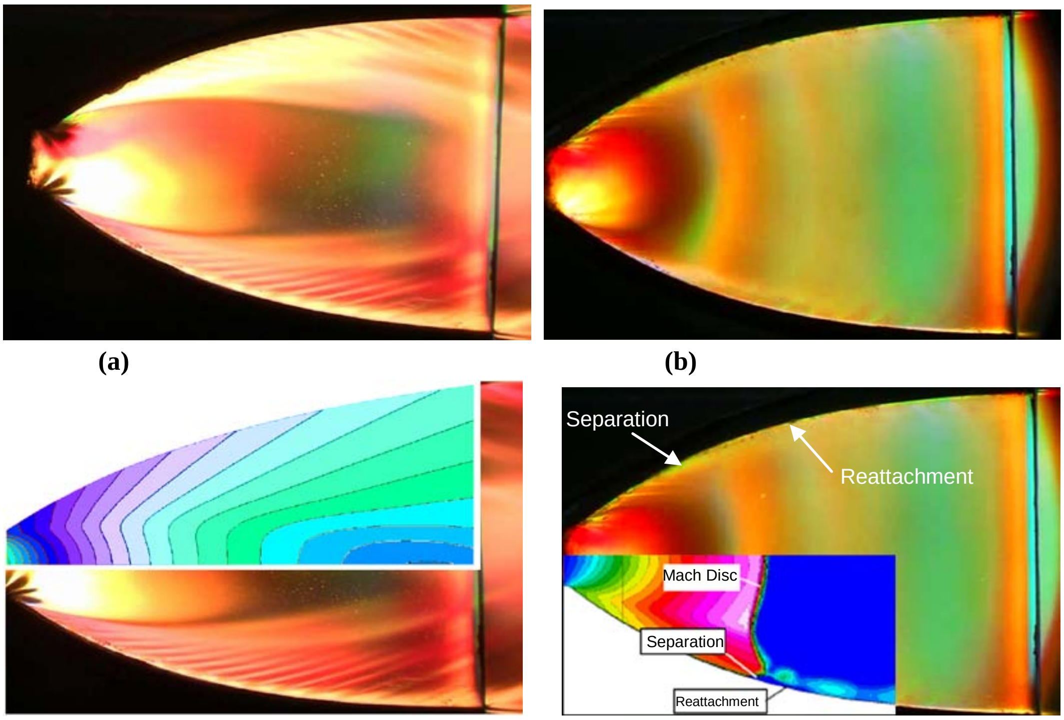

Fig.2 Experimental color Schlieren imaging of internal rocket nozzle flow, where flow is left to right. **(a)** Nominal maximum mach number (NMMN) ≅4.4, **(b)** NMMN ≅ 2; in **(c)** NMMN ≅4.4 and **(d)** NMMN ≅ 2 flow field images compared against CFD data adapted from Ostlund (2002).

In the central region of Fig. 2a, an internal shock is observed, with the central flow being decelerated near the exit via a mach stem.

Presented in Fig. 2b is a representative image of the shock structure at a lower stagnation (= tank) pressure. Weak oblique shocks along the wall and an expansion fan at the nozzle throat can again be seen. Here, the internal shock is truncated at a large internal cap shock (observable at about one-third of the way down the nozzle as a light cream colored vertical band). There are also regions of separation and reattachment along the walls from 35% to 55% of the length.

As a further demonstration of the system’s imaging performance, we present in Figs. 2c and 2d these experimental images superimposed on Computational Fluid Dynamics (CFD) results adapted from Ostlund (2002). His analysis of restricted shock separation (RSS) is representative of the problem of interest. While the planar nozzle in the experiment obviously differs from the circular nozzle modeled by Ostlund (2002), it is expected that flow structure observed in a planar nozzle will be *qualitatively* similar to that in difficult-to-image circular nozzles.

In conclusion, a simple, inexpensive, safe apparatus for carrying out imaging studies of high speed flows within nozzles, operating under the high nozzle pressure ratios characteristic of medium-to-large scale rockets, has been described. In addition to presentation of representative experimental results, a comparison with available CFD results indicates that the images provide useful *qualitative* information on high speed, high NPR flows in circular nozzles.

4. References

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