JOURNAL OF PROPULSION AND POWER
Vol. 25, No. 3, May–June 2009

Compressible Flow Structures Interaction with a Two-Dimensional Ejector: A Cold-Flow Study

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DOI: 10.2514/1.39315

An experimental study has been conducted to examine the interaction of compressible flow structures such as shocks and vortices with a two-dimensional ejector geometry using a shock-tube facility. Three diaphragm pressure ratios of $P_4/P_1 = 4$, 8, and 12 have been employed, where P_4 is the driver gas pressure and P_1 is the pressure within the driven compartment of the shock tube. These lead to incident shock Mach numbers of $M_s = 1.34$, 1.54, and 1.66, respectively. The length of the driver section of the shock tube was 700 mm. Air was used for both the driver and driven gases. High-speed shadowgraphy was employed to visualize the induced flowfield. Pressure measurements were taken at different locations along the test section to study the flow quantitatively. The induced flow is unsteady and dependent on the degree of compressibility of the initial shock wave generated by the rupture of the diaphragm.

I. Introduction

STUDIES of shocks expanding into confined regions lack detailed quantitative data of major flowfield features that evolve in time. The transient behavior of shock waves and detonations has been the subject of many investigations. These include phenomena such as shock reflection, diffraction, and shock/vortex interactions. Shock wave reflections have been studied both experimentally and analytically by Ben-Dor et al. [1], Ben-Dor and Takayama [2], and Henderson and Lozzi [3]. The shock diffraction pattern over corners at different Mach numbers has been studied experimentally by Skews [4,5] and Griffith and Brickl [6]. Shock diffraction from small to larger areas has been studied by a number of authors, such as Chang and Kim [7] and Jiang et al. [8]. The main focus of these studies has only been a specific aspect of shock wave behavior, that is, diffraction, reflection, or shock/vortex interaction.

Detonation diffractions from small to larger areas have especially attracted the attention of many researchers. Detonations are distinguished from shock waves by the presence of an intrinsic length scale associated with a reaction zone [9–11]. The study into the evolution of detonation waves that suddenly expand has been motivated not only by the need to suppress accidental detonations but also in the interest of the applicability of such flows to the concept of pulse detonation engines (PDEs) [12–19].

Pulse detonation engines are currently being investigated as a new technology for aerospace propulsion [20]. Because of the inherently unsteady nature of PDEs, one of the main challenges of making practical engines is minimizing the losses at the inlet and outlet. Ejectors are fluid pumps that are used to entrain secondary flows using a primary flow. For propulsion applications, this entrainment can augment thrust compared to that generated by the primary flow alone and thereby increase performance. Of course, high thrust augmentation for PDE-ejector applications is only achievable once the gas dynamics and the flow interactions of the PDE-ejector system are understood [21].

Nondetonational computational studies have highlighted the importance of the starting vortices, precursor shocks, and direct pressure loads created by the gas dynamic (shock-tube) processes within the ejector to the overall thrust-augmentation performance of the system. These data will be valuable for calibrating computational fluid dynamics codes and ultimately for the optimization of PDE-ejector configurations for propulsion applications [22].

The present study examines, both qualitatively and quantitatively, the interaction of compressible structures such as shocks and vortices with a 2-D ejector configuration. These structures are generated by the passage of shock waves through a converging nozzle with an ejector placed at the exit. The interaction of the flow features with the test section generates multiple shock waves which travel both upstream and downstream. The behavior of these shocks will have a significant impact in the performance of multicycle PDEs, especially on parameters related to the purging period where adequate pressure levels are vital [23] and where convergent nozzles are used at the nozzle exit to preserve chamber pressure. The presence of these shocks also plays an important role in the noise levels produced by PDEs which must meet standard noise regulations [24].

II. Experimental Setup

Experiments have been carried out using a cylindrical shock tube made of seamless pipe to generate the shock waves. The internal and external diameters of the shock tube were 30 and 38 mm, respectively. Driver gas pressures of $P_4 = 4$, 8, and 12 bar were examined, with the pressure in the driven section P_1 being ambient. Air has been used as both the driver and driven gases. Using Eq. (1), the driver pressures correspond to theoretical Mach numbers of $M_s = 1.31$, 1.49, and 1.61, respectively [25]:

$$\frac{P_4}{P_1} = \left[1 + \frac{2\gamma_1}{\gamma_1 + 1}(M_s^2 - 1)\right] \times \left[\frac{1}{1 - (\gamma_4 - 1/\gamma_1 + 1)(a_1/a_4)[M_s - (1/M_s)]}\right]^{2\gamma_4/\gamma_4 - 1} \tag{1}$$

where M_s is the incident shock Mach number, γ is the ratio of specific heats, and a is the velocity of sound. The subscripts 1 and 4 correspond to the driver and driven gases, respectively.

The driver length was 700 mm. An industrial film diaphragm divided the two sections of the shock tube. The thickness of the diaphragm used was 23, 55, and 75 μm for $P_4/P_1 = 4$, 8, and 12, respectively. This is the minimum thickness that can sustain the desired pressure without spontaneously rupturing. The bursting of the diaphragm was initiated manually with a plunger. The setup is similar to that described in [25–27].

To study the different aspects of shock wave behavior, the model shown in Fig. 1 was employed [28]. This is attached to the circular shock tube via an adaptor, which gradually changes the nozzle shape

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Received 24 June 2008; revision received 1 October 2008; accepted for publication 1 October 2008.

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