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Investigation of the Rocket Induced Flow Field in a Rectangular Duct

D. Brian Landrum,* James Lambert,** Mignon Thames,** and Clark Hawk®
Propulsion Research Center
University of Alabama in Huntsville
Huntsville, AL 35899

Introduction

Rocket-Based Combined Cycle (RBCC) concepts attempt to improve the performance of launch vehicles at all points in the launch trajectory and make highly reusable launch vehicles a reality. The Aerojet Strutjet RBCC concept consists of a variable geometry duct with internal, vertical struts that functions in ducted rocket, ramjet, scramjet, and pure rocket modes.[1] These struts have rocket and turbine exhaust nozzles imbedded within them. The rocket flows create an ejector effect with the ingested air at subsonic flight velocities. In ramjet and scramjet modes, the fuel rich nozzle flows react with the ingested air producing an afterburner effect.

Under a NASA Marshall Space Flight Center contract, the UAH Propulsion Research Center (PRC) has designed and built a Strutjet simulation facility. A scale model of a single strut has been built and is undergoing cold-flow testing to investigate the mixing of the rocket and turbine exhausts with the ingested air. A complementary experimental program is also underway to examine the induced flow-field generated by rocket nozzles confined in a rectangular duct. Characterizing the induced flow behavior is critical to understanding and optimizing the performance of future Strutjet-based RBCC propulsion systems. The proposed paper will present results from the rocket induced flow investigation.

Experimental Facility and Model Design

The rocket and turbine gas simulants are air and carbon dioxide, respectively. This choice was based on a desire to match the convective Mach numbers of the full-scale system.[2] The air supply system is shown schematically in Fig. 1. High-pressure air is delivered to the embedded rocket nozzles from a 500-ft^3 tank operating at a nominal pressure range of 1100 to 925 psia in the blowdown mode. The air is heated by a 260-kW heater to approximately 600 °R. A flowrate of up to 4 lbm/sec can be delivered. The carbon dioxide is delivered from a pallet system at approximately 100 psia and 760 °R. A flowrate of approximately 0.1 lbm/sec is used for this study.

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* Associate Professor, Department of Mechanical and Aerospace Engineering. AIAA Senior Member.
** Graduate Student, Department of Mechanical and Aerospace Engineering.
® Director and Professor, Department of Mechanical and Aerospace Engineering. AIAA Associate Fellow.
[1] Bulman, M. and Siebenharr, A., "The Strutjet Engine: Exploding the Myths Surrounding High Speed Airbreathing Propulsion," *AIAA Paper 95-2475*, July 1995.
[2] Hawk, C.W., Landrum, D.B., Spetman, D., and Parkinson, D., "Mixing of Supersonic Streams," *Proceedings of the 1997 JANNAF Joint Meeting of the Combustion, Propulsion System Hazards, and Airbreathing Propulsion Subcommittees*, West Palm Beach, FL, October 27 – 31, 1997.

The 1/6 scale strut model is installed in a rectangular (4" × 4") plexiglass duct (Fig. 2). As shown in Fig. 3, the duct is open at each end with a contoured inlet and a cylindrical diffuser. Another view of the two-dimensional contoured inlet is shown in Fig. 4. An aerodynamic fairing covers the upstream end of the strut. The duct has quartz side windows to allow the use of optical diagnostic techniques.

As shown in Fig. 2, the two rocket nozzles have square exits with an area ratio of 4.529. The thin, two-dimensional turbine exit is embedded in the rocket nozzles. The turbine nozzle has an area ratio of 1.126. The rocket nozzles were designed to exit at standard atmospheric pressure (14.7 psia). The turbine was designed to exit at approximately twice this value.

Comparison of Current Experiment to Previous Research

An extensive literature search indicated that there are significant differences between the current investigation and previous ejector studies. Previous efforts investigated only axisymmetric configurations for the mixing tubes and the nozzles. The current experimental setup consists of a rectangular duct and square rocket nozzle exits. The strut represents a much larger blockage to the induced flow-field.

The UAH rocket nozzle chamber conditions and flow rates are also much higher than the conditions previously investigated. In the classic work by Fabri and Sistrunk[3] the ratio of rocket chamber total pressure to free stream total pressure was limited to a maximum $P_{\mathrm{chamber}}/P_{\mathrm{freestream}} = 6$. The current system has a maximum ratio of $P_{\mathrm{chamber}}/P_{\mathrm{freestream}} = 40$. Also, NASA funded studies in the 1970's on multi-nozzle ejector systems with a circular mixing tube had maximum nozzle mass flow rates of 0.12 lbm/sec.[4] A total nozzle mass flow rate of 4 lbm/sec is used in the UAH Strutjet study.

The objectives the UAH experiments are (1) to examine the induced airflow due to the ejector effect and (2) to examine the growth of the boundary layer in the strut/sidewall gap. This information will be used to interpret data obtained on the downstream mixing of the ingested air and the rocket exhausts. The study includes a series of pressure measurements just upstream of the strut and boundary layer surveys in the gap region.

Current Results

The duct inlet and diffuser have been instrumented with a series of pitot and static pressure tubes. A Pitot-static tube is installed in the aerodynamic fairing upstream of the strut. The differential pressure reading from this tube (which is approximately the duct flow dynamic pressure) provides a means for evaluating the induced airflow in the duct. Figure 5 shows a typical output for the differential pressure overlaid on a plot of the embedded rocket chamber pressure as the chamber pressure is ramped up. Note that the differential pressure is multiplied by a factor of 200. The pitot-static pressure peaks at approximately 1.5 psia when the corresponding rocket chamber pressure is approximately 350 psia. As the rocket chamber pressure is increased to the 600 psia operating condition, the pitot-static pressure remains relatively constant indicating a choked condition in the inlet duct.

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[3] Fabri, J., and Siestrunck, R., "Supersonic Air Ejectors," Advances in Applied Mechanics, Vol. V, Academic Press, New York, 19958, pp. 1- 34.

[4] NASA-CR-1602

The choking of the induced airflow can be produced by the geometric minimum area at the strut gap or a Fabri mass choke in the duct downstream of the nozzle exit plane. Both phenomena are influenced by the boundary layer thickness in the duct. Boundary layer survey ports and a static pressure tap have been installed in the strut/sidewall gap region of the duct. A preliminary total pressure survey in the gap region is shown in Figure 6. Both the forward traverse from sidewall to strut and the reverse traverse from the strut back to the sidewall are shown. The symmetry indicates the level of repeatability of the data. The pressure traverse data provide a means of estimating the displacement thickness of the boundary layer and examining the reduction of the effective area in the gap region. The data can also be used to determine if the interaction of the rocket exhaust streams and the duct sidewalls are influencing the upstream boundary layer growth.

Anticipated Results

A series of Strutjet test runs are currently being performed. The preliminary strut/sidewall gap pressure surveys were performed with a manual traversing mechanism that made determination of actual spatial location difficult. An automated traversing mechanism is being installed with digital position readout. Higher resolution gap pressure surveys will be performed and discussed in the final paper.

Optical components to take a shadowgraph image of the mixing region have also been installed. These images will be used to identify any mixing and shock structures that can be correlated with the measured wall and gap pressure measurements.

Finally, a less complex strut with a single rocket nozzle is being designed. A series of tests is planned to investigate the rocket-induced flow in this configuration. This data can be directly compared to the historical studies that used axisymmetric nozzle and duct configurations. These results will also be presented in the final paper.

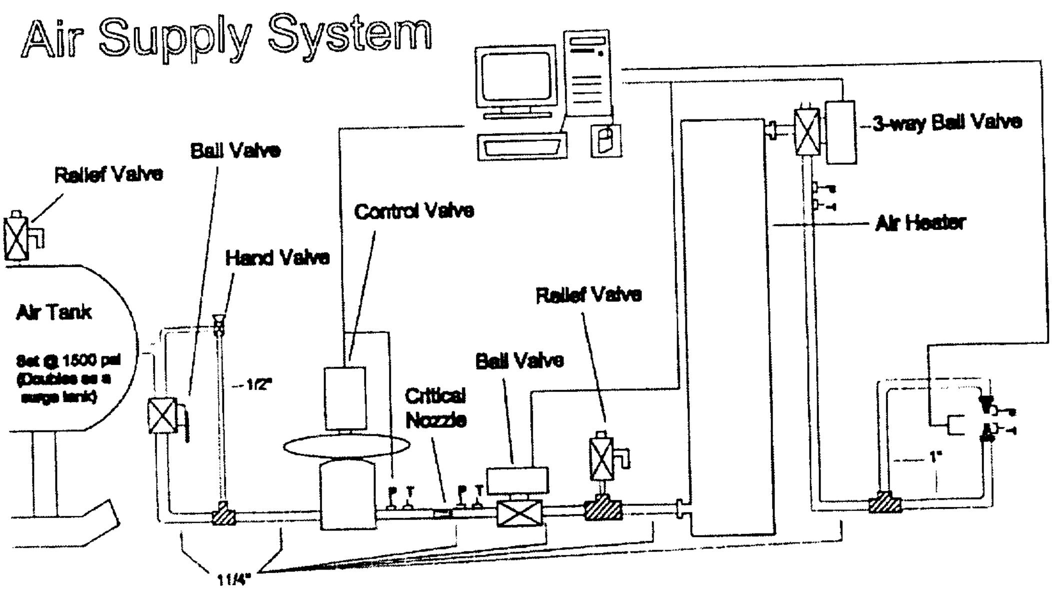

Fig. 1 Air supply system for UAH Strutjet simulation facility.

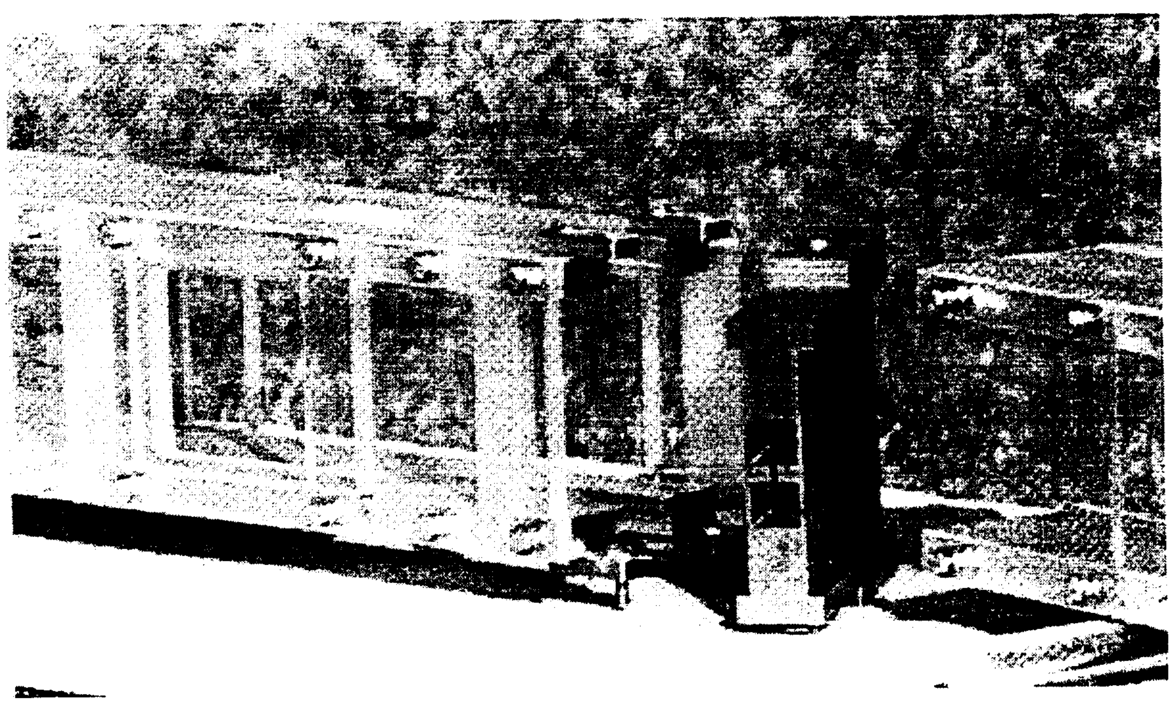

Fig. 2 Plexiglass duct and Strut model. Note square rocket nozzle exits and embedded turbine nozzle exit.

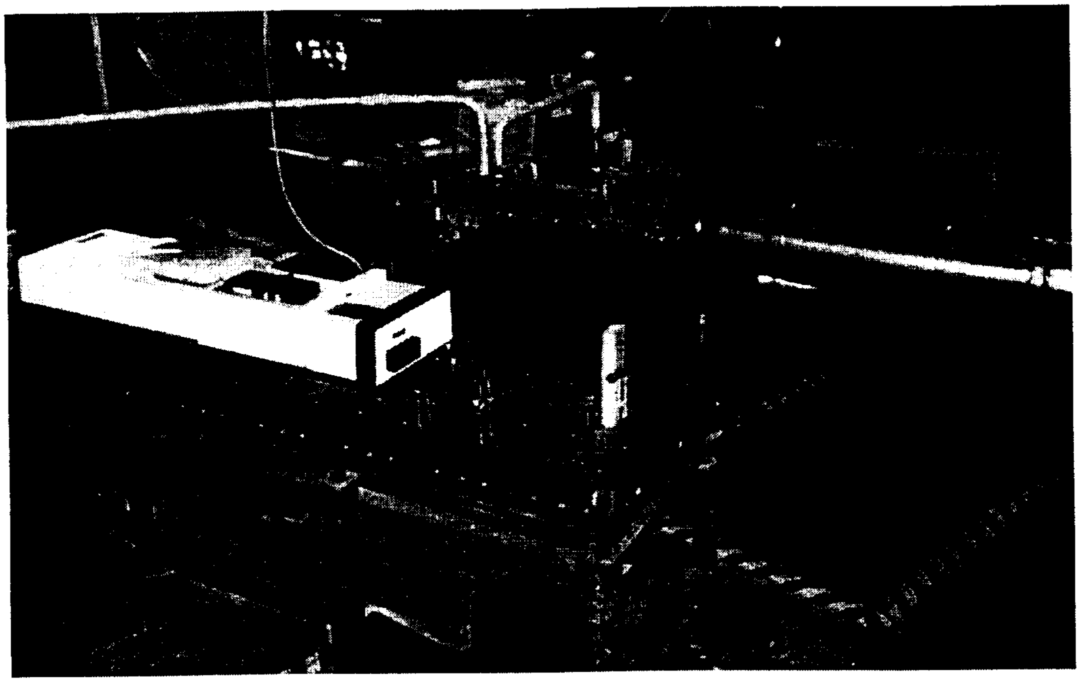

Fig. 3 UAH Strutjet simulation facility showing contoured inlet, duct, diffuser, and laser diagnostics table.

Fig. 4 UAH Strutjet simulation facility showing two-dimensional contoured inlet.

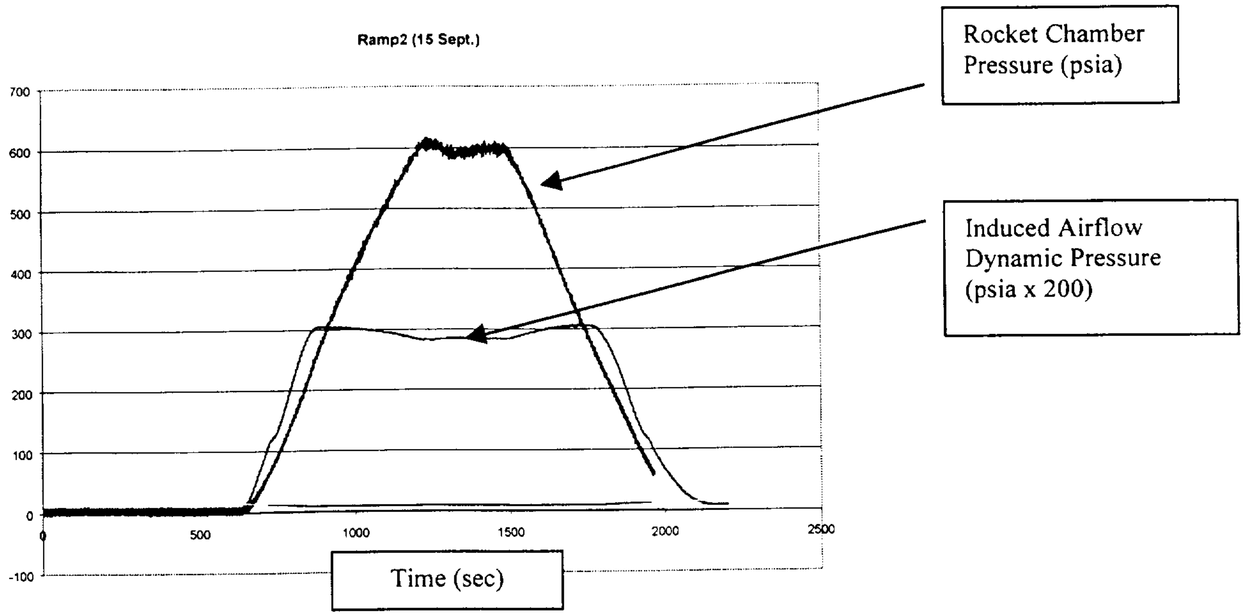

Fig. 5 Rocket chamber and induced flow dynamic pressure histories.

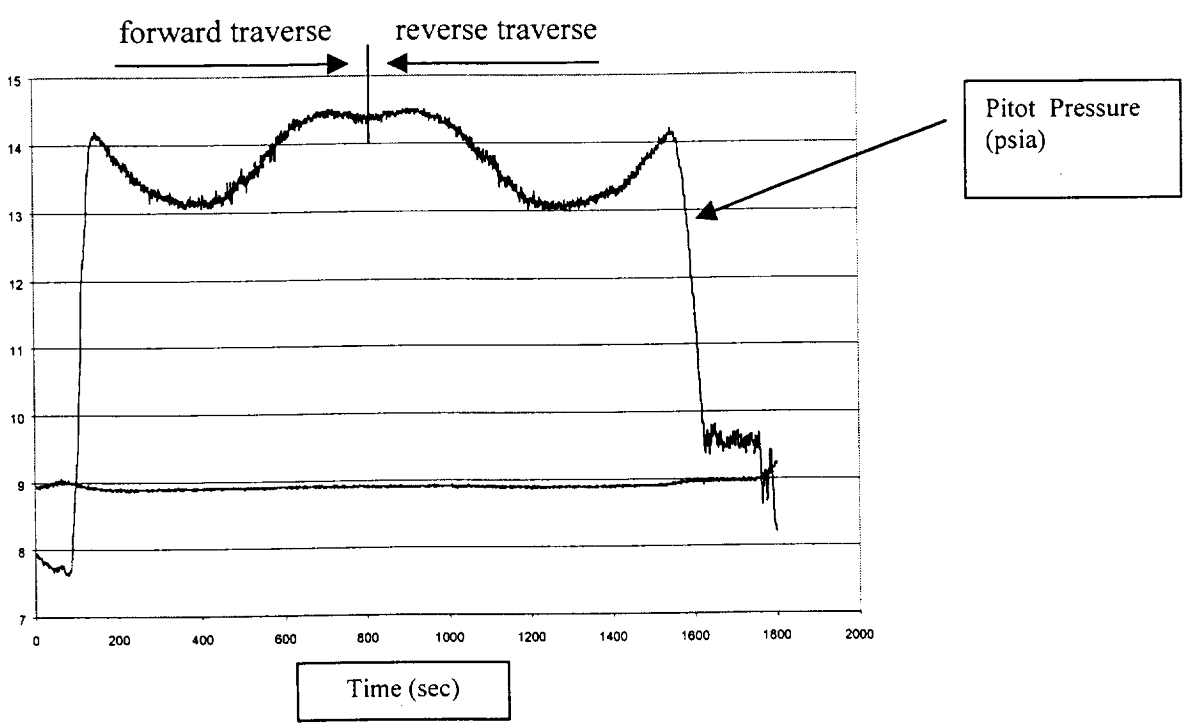

Fig. 6 Sidewall/strut gap total pressure traverse. Rocket chamber pressure of 600 psia.