CONF PAPER
IN-20
376 558

Mixing of Supersonic Streams

Clark W. Hawk[*], **D. Brian Landrum**[†]
Matthew Turner[#], **David K Wagner**[‡], **and James Lambert**[**]
University of Alabama in Huntsville

Abstract

The Strutjet approach to Rocket Based Combined Cycle (RBCC) propulsion depends upon fuel-rich flows from the rocket nozzles and turbine exhaust products mixing with the ingested air for successful operation in the ramjet and scramjet modes. A model of the Strutjet device has been built and is undergoing test to investigate the mixing of the streams as a function of distance from the Strutjet exit plane.

Initial cold flow testing of the model is underway to determine both, the behavior of the ingested air in the duct and to validate the mixing diagnostics. During the tests, each of the two rocket nozzles ejected up to two pounds mass per second into the 13.6 square inch duct. The tests showed that the mass flow of the rockets was great enough to cause the entrained air to go sonic at the strut, which is the location of the rocket nozzles. More tests are necessary to determine whether the entrained air chokes due to the reduction in the area of the duct at the strut (a physical choke), or because of the addition of mass inside the duct at the nozzle exit (a Fabri choke). The initial tests of the mixing diagnostics are showing promise.

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 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. As shown in Fig. 1, the four primary rocket flows exit at the end of the strut with three turbine exhaust nozzles in between them. The Strutjet is designed to mix the fuel rich flows (rocket and turbine exhaust gases) in the vertical direction before significant combustion occurs with the ambient air. After the hot, fuel rich flows are mixed (and after the shear layers between the nozzle flows and the ambient air reach the walls of the duct), air breathing combustion begins. The combustion products thermally choke and are expanded through the duct's nozzle that is provided by the engine and, to a large part, by the aft air frame.[2]

Approach

The approach to evaluating the mixing process is experimental in nature. A scale model consisting of a single pair of rocket nozzles with a turbine exhaust nozzle between them (Figure 2) permits investigation of the mixing process at a manageable scale. The model is mounted in a rectangular duct. The lateral spacing between the model and the duct walls was scaled to the distance between the full-scale model and the centerline between adjacent struts. In this respect, the test configuration places a solid wall where a gas interface would be in the full-scale device. The simulated rocket nozzles are supplied

---

[*] Professor of Mechanical & Aerospace Engineering and Director, Propulsion Research Center
[†] Associate Professor of Mechanical & Aerospace Engineering
[‡] Undergraduate Research Assistant
[#] Undergraduate Research Assistant
[**] Graduate Research Assistant

with heated air at approximately 600 psia and 600 °R. The simulated turbine exhaust nozzle is supplied with heated CO_2 that has been seeded with laboratory grade acetone.

The full scale mixing process is modeled based upon similitude of the convective Mach Number between the turbine exhaust and rocket nozzle flows. This is achieved in the cold flow test by use of hot (600°R) air as the rocket exhaust simulant and hot (760°R) carbon dioxide as the turbine exhaust gas simulant[3].

The measure of the mixing process is achieved through use of Laser Induced Fluorescence (LIF). The carbon dioxide gas is seeded with laboratory grade acetone. The acetone vapor is excited at a wavelength of 266 nm and the fluorescent signal is emitted over a wide spectral range (~350 nm to 550 nm). The fluorescent signal will be collected over a bandwidth of 485-495 nm, eliminating interference from scattered laser light. Acetone fluorescence is linear with respect to incident laser intensity and acetone mole fraction[4]. Collision quenching of acetone fluorescence is intra molecular[4]. The fluorescence is, therefore, independent of temperature and local gas composition. Thus, quantitative information is readily obtained from the collected images.

The acetone fluorescence has a lifetime of less than 4 nanoseconds. Acetone also phosphoresces at wavelengths similar to the fluorescence, albeit at a much greater lifetime of about 200 microseconds. The phosphorescence interference is rendered negligible by the gating of the intensified camera at 10 microseconds. This also eliminates background interference

The Nd:YAG laser output of 1064 nm is frequency quadrupled to produce a 266-nm laser beam. The 1064 nm and 532 nm components of the beam will be separated into a beam dump while the 266-nm beam is sent to the test section. The beam is formed into a laser sheet approximately 2 inches high and 500 micron thick by a series of cylindrical lenses. The beam then passes through a 4"x4" fused silica window into the duct. The beam traverses the model cross section of concern and passes through the 4"x4" window on the other side.

The acetone fluorescent signal is observed by a Princeton ICCD camera. The intensity of the fluorescence is directly related to the acetone concentration in the flow.

Diagnostic Tests

The diagnostic methodology has been validated in initial testing. Figure 3 shows the observed acetone fluorescence from a test in which the turbine exhaust nozzle alone is flowing air with the acetone seedant. Images were recorded both with the airflow alone (Fig. 4) and with the airflow plus seedant (Fig. 5). The former was subtracted from the latter to obtain the image shown in figure 3. The flow is expanding vertically as expected with slight lateral expansion at the upper and lower extremities of the nozzle exit plane. This is much as expected.

Ejector Tests

We conducted a series of tests to determine the behavior of the model in conjunction with the duct to measure the magnitude of the ingested flow as a result of the ejector action of the rocket exhaust.

The model is located inside of a duct, which is 4 inches high by 3.4 inches wide throughout its 6 feet in length. The model is located approximately 30 inches from the open inlet to the duct. The duct exit is also open to atmosphere. Just upstream of the model is a fairing to streamline flow around the model. A Pitot tube was placed through the fairing, on the centerline of the duct (Figure 6) for these tests,. It protruded into the flow about 1-inch upstream of the fairing. The Pitot tube had both a total pressure port and a static pressure port. Two pressure transducers were used to measure the flow– one was a standard 0-25 psia transducer and the other was a 0-15 psid differential transducer.

Bernoulli's equation was used to determine the ingested mass flow rate from the measured pressure differential. Assuming the initial velocity of the entrained flow is negligible and incompressible flow, the velocity at the Pitot probe can be calculated by the equation:

$$V = \sqrt{\frac{2(p_0 - p)}{\rho}}$$

Ingested mass flow rate can then be determined by:

$$\dot{m} = \rho A V$$

The mass flow of the rocket nozzles was determined using the equation:
:

$$\dot{m}_{air} = \frac{(0.532)(A^*)(P_0)}{\sqrt{T_0}}$$

The constant 0.532 accounts for the effect of the ratio of specific heats and the molecular weight of air. A^* is the cross sectional throat area of the nozzle, P_0 is the chamber pressure of the nozzle, and To is the total temperature of the nozzle flow. The model was supplied with high-pressure (600 psia) air. The air temperature was approximately 480 °R. The predicted a rocket nozzle flow was 2 lbm/sec. (The sensitivity of the flow to the measrueed temperature was calculate. A temperature difference of 20 degrees results in a 2% variation in the flowrate.)

The rocket chamber pressure history is shown in Figure7. The pressure ramps up to the set point of 600 psia in approximately 30 seconds and then decays The pressure differential measured upstream of the faring is shown in Figure 8. It reaches a maximum of about 0.9 at 15 seconds and remains fairly constant We used the differential pressure to calculate the mass flowrate of the ingested air. The data are plotted versus the total mass flowrate through the rocket nozzles in Figure 9. These data show that the ingested flow rate in the duct reaches a maximum when the rocket flows are about 2 lbm/sec and remains essentially constant as the rocket flowrate increases beyond that value. The data were calculated both for the pressure increase and the pressure decay in the rocket plenum. These reflect some slight discrepancies, but a consistent behavior pattern.

The behavior seen is indicative of choked flow in the duct. The induced flow is variable with increasing flow of the primary nozzles and remains essentially constant beyond some primary flowrate. The reasons for this behavior are presently under investigation. We might be observing a choked flow that results from the change in area in the vicinity of the strut. We are probing the flow at this location to measure the boundary layer thickness at the model exit as a means to determine if the area change is responsible. The other possibility is that the flow choking is being realized as a result of the mass addition from the primary nozzles. The planned measurements are intended to answer the question as to which mode is present.

Summary

An experimental program has been initated to investigate the mixing processes associate with the strutjet concept. Flow testing has begun on this program. The acetone PLIF technique appears to be behaving as anticipated and the UAH team has established the procedures and equipment to produce the desired data.

Test results showed that the ingested air in the duct was experiencing choked flow. This was not anticipated and requires further study to understand its causes and its implications to a hot firing application.

References

[1]Bulman, M. and Siebenhaar, A., "The Strutjet Engine: Exploding the Myths Surrounding High Speed Airbreathing Propulsion," AIAA Paper 95-2475, July 1995.

[2]Bulman, M., Private Communication, Aerojet, September 6, 1996.

[3] Hawk, C. W., Landrum, D. B., Spetman, D. M., and Parkinson, D., "Mixing of Supersonic Streams", 1997 JANNAF 34th Combustion Subcommittee, Propulsion Systems Hazards Subcommittee and AirBreathing Propulsion Subcommittee, Joint Meeting, October 1997

[4]Lozano, A., Yip, B., and Hanson, R. K., "Acetone: a Tracer for Concentration Measurements in Gaseous Flows by Planar Laser-Induced Fluorescence," *Experiments in Fluids*, Vol. 13, 1992, pp. 369-376.

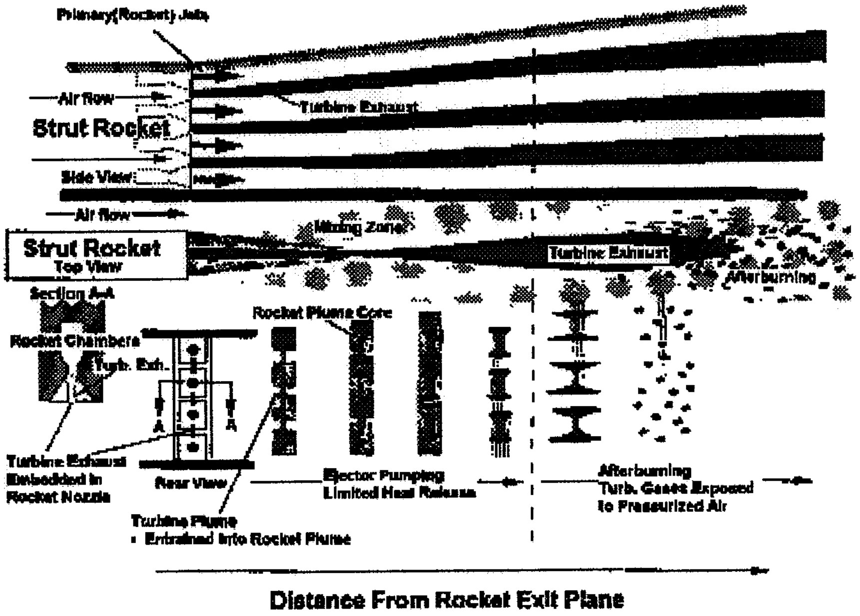


Figure 1

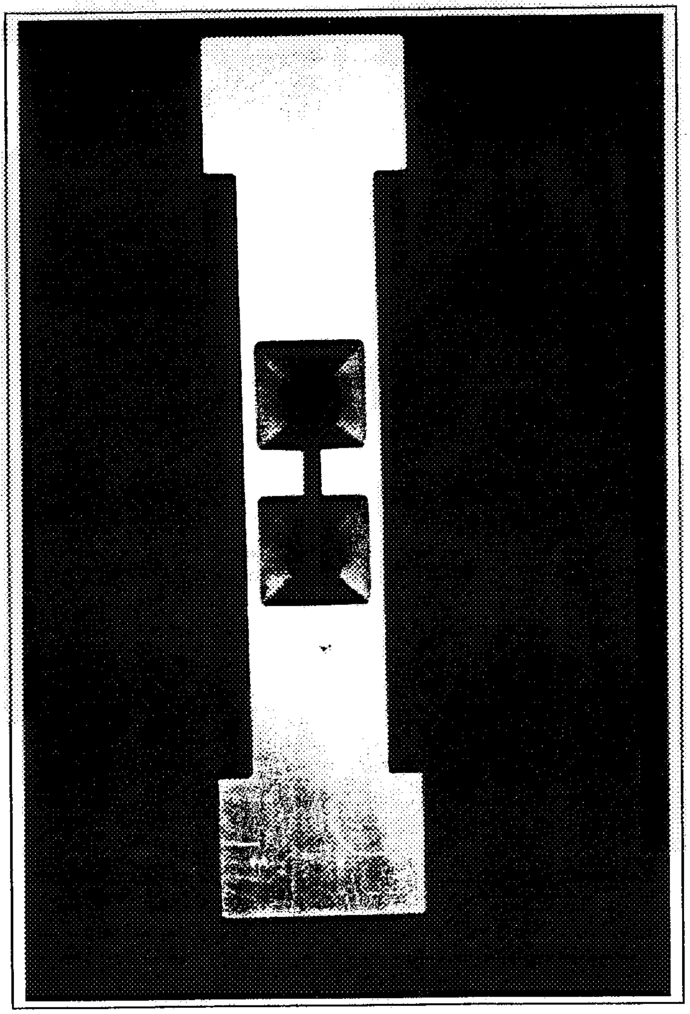
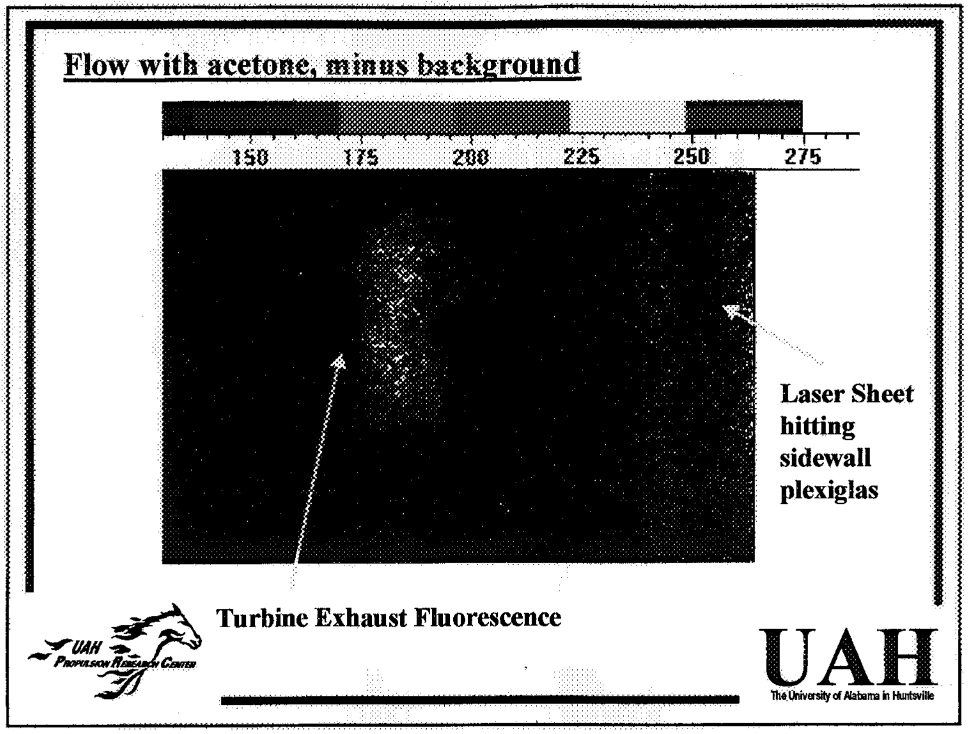


Fig 2



Flow with acetone, minus background

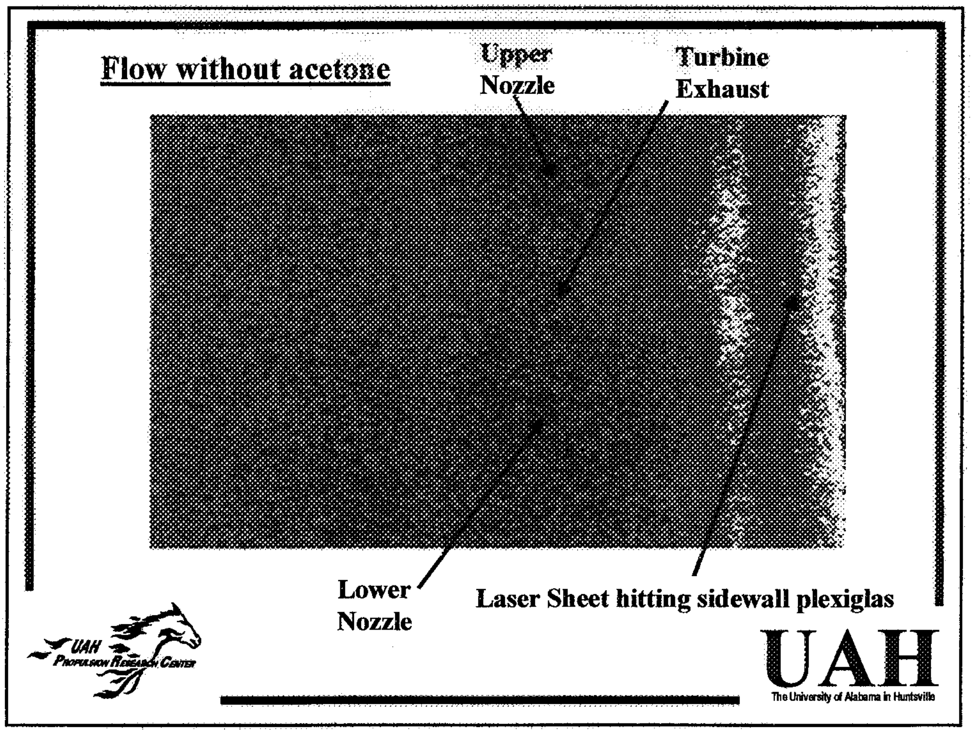
Laser Sheet hitting sidewall plexiglas

Turbine Exhaust Fluorescence

UAH Propulsion Research Center

UAH
The University of Alabama in Huntsville

Fig 3



Flow without acetone

Upper Nozzle

Turbine Exhaust

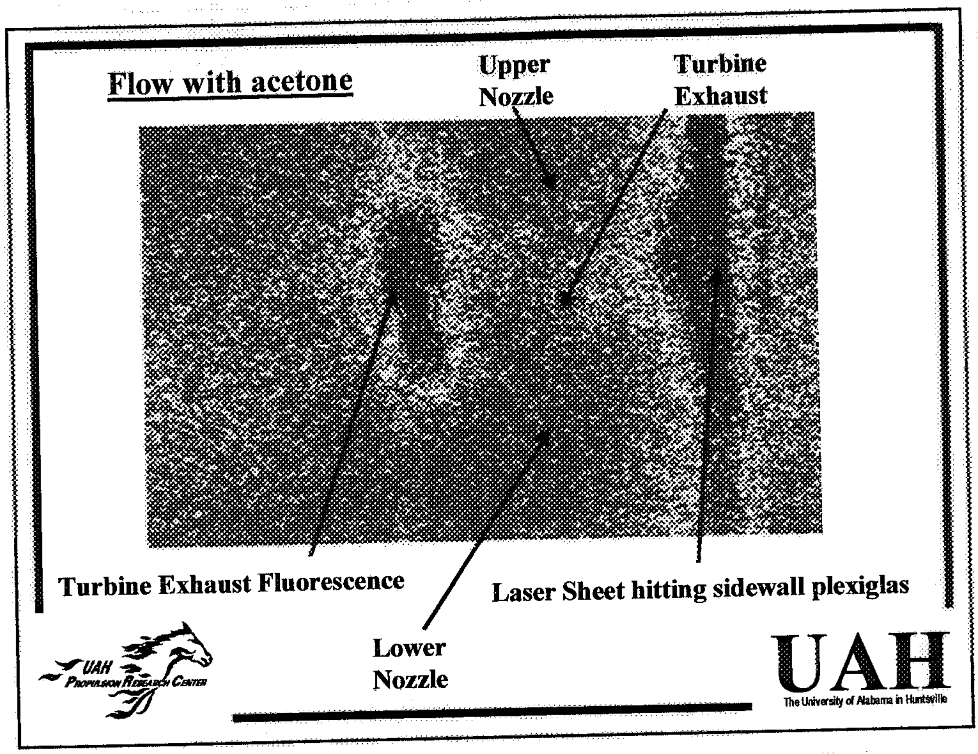
Lower Nozzle

Laser Sheet hitting sidewall plexiglas

UAH Propulsion Research Center

UAH
The University of Alabama in Huntsville

Fig 4



Flow with acetone

UAH Propulsion Research Center

UAH
The University of Alabama in Huntsville

Fig 5

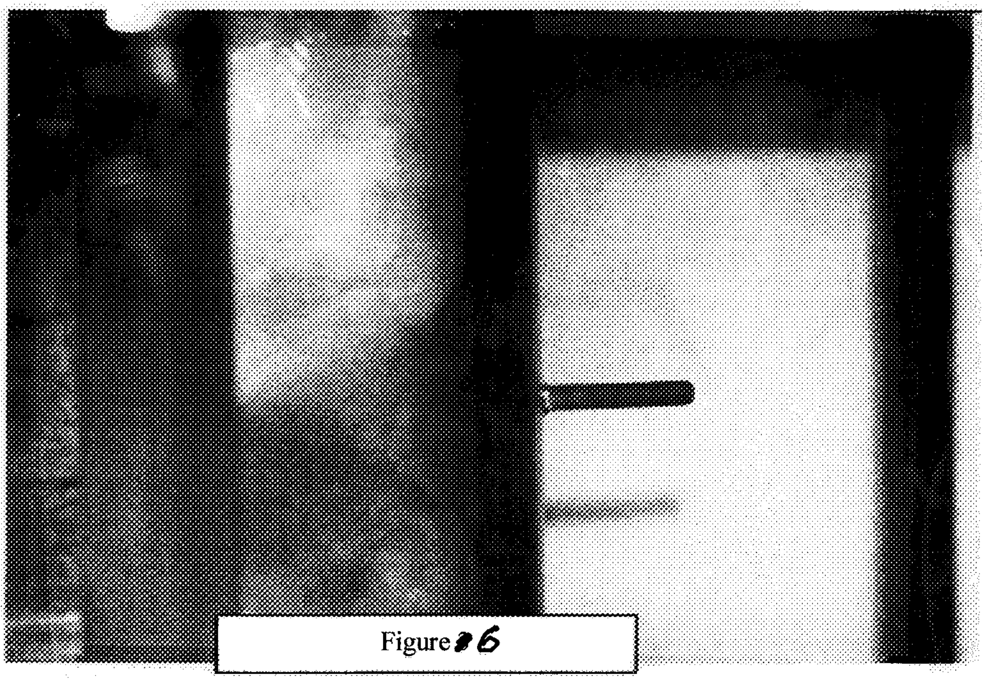


Figure 6

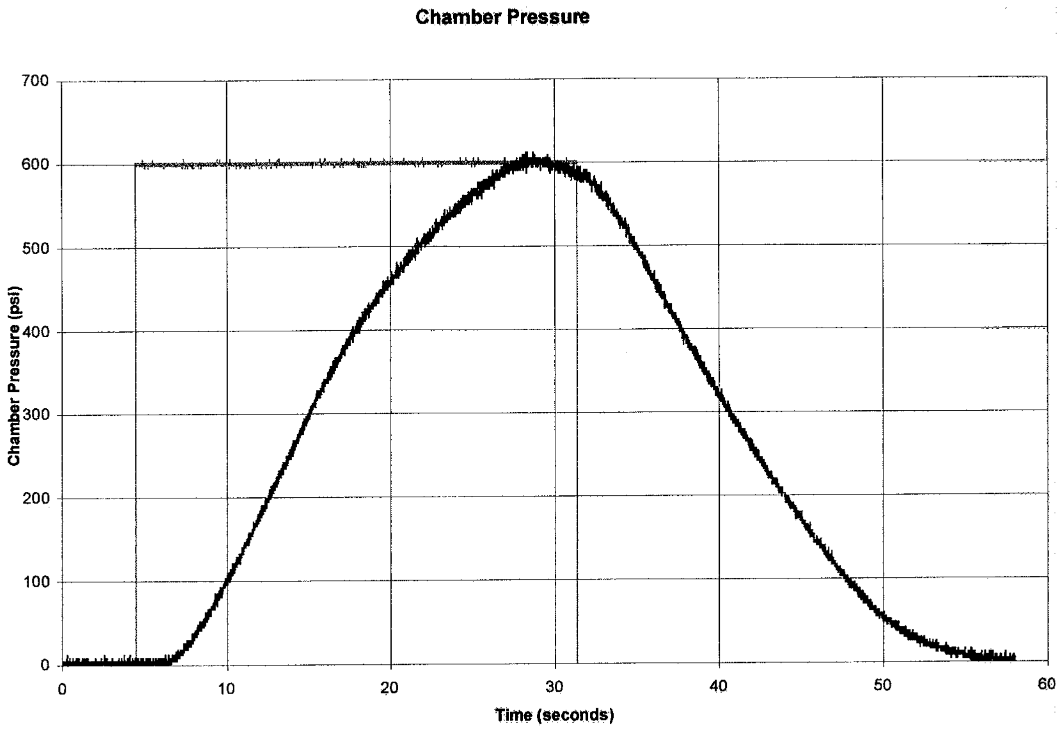

Chamber Pressure
700
600
500
400
300
200
100
0
Chamber Pressure (psi)
0
10
20
30
40
50
60
Time (seconds)

Fig 7

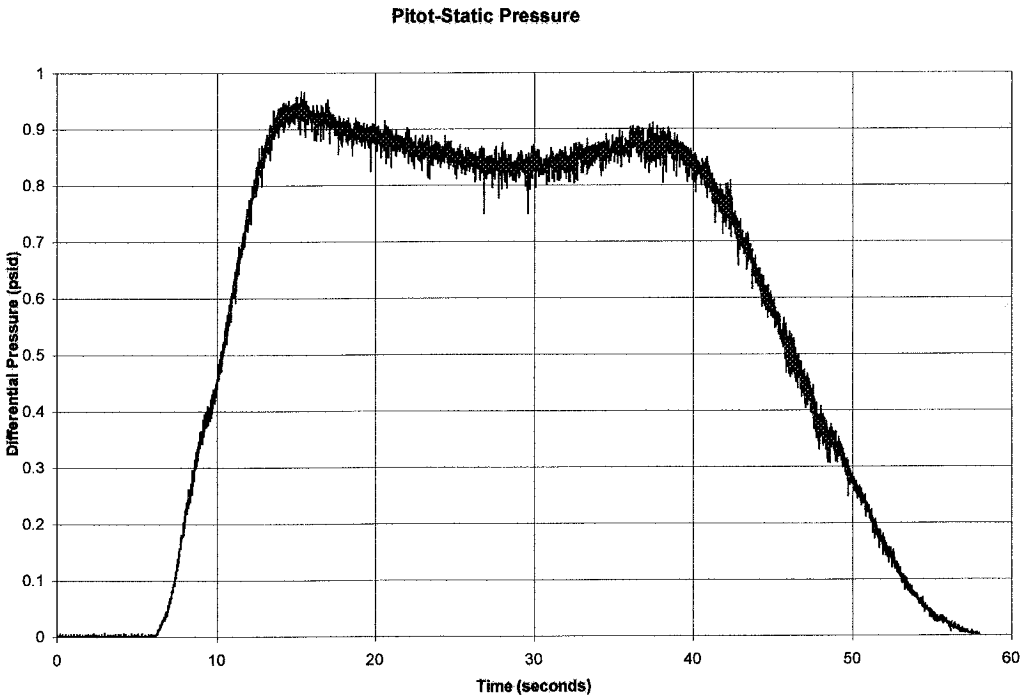

Pitot-Static Pressure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Differential Pressure (psid)
0
10
20
30
40
50
60
Time (seconds)

Fig 8

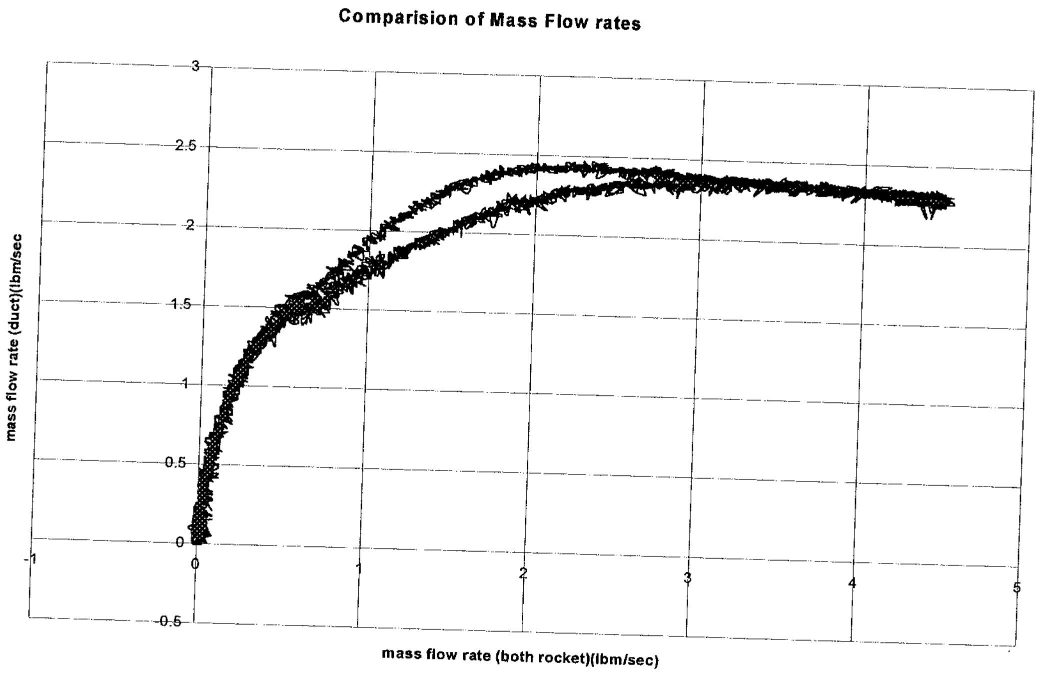


Figure 9. Mass Flow of Duct Compared to Mass Flow of both Rockets

Fig 9