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Constance Meadors and A. B. Wright
Department of Applied Science
2801 South University Ave.
University of Arkansas at Little Rock
Little Rock, Arkansas 72204

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Constance Meadors*, A. B. Wright†
Department of Applied Science
University of Arkansas at Little Rock
Little Rock, AR 72204

Abstract

A gas extraction system (GES) has been designed for use with the hybrid rocket facility at the University of Arkansas at Little Rock (UALR) for spectroscopic analysis of rocket plumes. While monitoring gas flowrate and pressure, the GES extracts gases from the hybrid rocket plume and transports them to a mass spectrometer. This project focuses on the design and construction of a gas extraction probe (GEP) prototype capable of extracting gases directly from the plume. Gas dynamics equations were used to design the GEP which consists of a converging throat tap nozzle and a venturi-type U-arm. The GEP has a throat diameter of 0.25 inches and an entrance diameter of 0.625 inches. The probe is 1.125 inches long. The probe was tested with air to verify design assumptions. Flow rate through the U-arm, throat pressure, and inlet pressure were measured. Inlet and throat Mach numbers were calculated to determine at what point choked flow at the nozzle occurs.

Introduction

The University of Arkansas at Little Rock (UALR) has designed and built a labscale hybrid rocket facility, which is shown schematically in Figure 1. [1] A hybrid rocket motor employs a cylindrical, hollow, solid fuel grain through which oxygen flows. It combines advantages of a liquid propellant motor (start-stop-restart, throttle capabilities, and safety) with those of solid propellant motors (less plumbing and higher propellant density). Hybrids use unconventional fuels, such as hydroxl-terminated polybutadiene (HTPB) and methyl methacrylate. Since pure oxygen is used as the oxidant, hybrids burn at high temperatures. These two factors may lead to undesirable exhaust constituents.

NASA's John C. Stennis Space Center (SSC) has done extensive research in the area of plume spectroscopy. [2] SSC has indicated that one of its priorities for its hybrid rocket programs is identification of constituents and amounts present in the exhaust gases. By making measurements along the plume, SSC will be able to monitor rocket engine health and meet EPA requirements. NASA currently uses Computational Fluid Dynamic (CFD) models to predict concentrations of exhaust constituents. Validating NASA's computer model of hybrid rocket combustion and flow will satisfy EPA requirements with more realistic safety factors on the rocket's performance envelope. If large-scale hybrid rockets are used for propulsion, the environmental effects due to exhaust must be quantified.

SSC also uses the non-invasive instrumentation and measurement techniques to monitor and diagnose failed components. NASA studies indicate that plume spectroscopy can be successfully used in monitoring the levels of metals that may be found in the plumes of rocket motors [2]. It is possible to monitor the health of the engine during operation and, by quantifying metals detected in the plume, determine excessive wearing of engine components. This method of monitoring the engine aids in inspection and flight certification of the Space Shuttle Main Engine (SSME). It may also be used to monitor future hybrid flight systems

The purpose of this research is to design a gas extraction system (GES), which will continuously extract gases from the hybrid rocket plume and transport them to a mass spectrometer (see Figure 1). The probe will be inserted in the plume so as to minimally disturb the flow pattern. The moving exhaust gases will drive a secondary flow through the probe's U-arm (see Figure 2). This paper focuses on the design of the gas extraction probe (GEP).

Design

Gas Extraction System

The gas extraction system consists of a gas collection unit (GCU), a gas flow line (GFL), and a Finnegan 5100B mass spectrometer (see Figure 1). The GCU removes gases from the plume of the hybrid rocket and transports them to the mass spectrometer via the GFL.

The GES is designed to meet hybrid rocket plume and mass spectrometer interface requirements. For

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* Graduate Student, student member, AIAA

† Assistant Professor, associate member, ASME

plume insertion, the design specifications of the GES are minimal flow disturbance and continuous sampling. Temperature, pressure, and Mach number are determined from the hybrid rocket plume. The hybrid rocket plume has a 3000°C temperature [4], 30 psi stagnation pressure, and a Mach number varying between 0.5-1.5. Mass spectrometer interface requirements are 20-25mL/min inlet flow rate and 10^{-5} Torr vacuum pressure.

Gas Collection Unit

A diagram of the GCU is shown in Figure 2. The GCU consists of a high temperature venturi-based probe, a U-arm, and measurement instrumentation. When the probe is inserted into the plume, the probe extracts gases. The pressure differential between the U-arm inlet and the nozzle throat forces a small metered flow around the U-arm. A "T" junction removes plume constituents in small amounts via a capillary tube and carries them to the mass spectrometer.

Gas Collection Probe

A converging nozzle is designed using one-dimensional, isentropic, compressible flow assumptions. [3] Given constant Mach number, M, stagnation pressure, P_t, and specific heat, γ, the static pressure is given by:

$$P = P_t\left[1 + \frac{\gamma - 1}{2}M^2\right]^{\frac{\gamma}{1-\gamma}}. \qquad (1)$$

The ratio between current area, A, and the area at which Mach number is 1.0, A^*, is given by:

$$\frac{A}{A^*} = \frac{1}{M}\left[\frac{\frac{\gamma+1}{2}}{1 + \frac{\gamma-1}{2}M^2}\right]^{\frac{\gamma+1}{2(1-\gamma)}}. \qquad (2)$$

For test purposes, the GCP was designed with an inlet Mach number of 0.01 and a stagnation pressure of 30psi. The area ratios and pressures were determined by equations 1 and 2 (see Figure 3). The GCP is made of aluminum with an inlet diameter of 0.625 inches and a throat diameter of 0.25 inches, yielding an area ratio, $\frac{A}{A^*}$, of 6.2. The probe has two holes 0.345 inches apart bored into it; one near the inlet and the other at the throat. Each has a diameter of 0.125 inches. The probe is 1.125 inches long.

U-arm

The U-arm is designed similar to the old carburetor venturi meter (see Figure 2). Gases enter the probe and flow through the U-arm. Assuming frictionless flow through th U-arm, the volumetric flowrate, Q, is expressed as a function of pressure difference, $P_1 - P_2$, by using Bernoulli's equation. [5] The volumetric flow rate through the arm is characterized by :

$$Q = A\sqrt{\frac{2(P_1 - P_2)}{\rho}}. \qquad (3)$$

The U-arm is instrumented with two pressure transducers to measure inlet pressure, P_1, and throat pressure, P_2. It is also instrumented with an inline flowmeter. The U-arm is made of 1/8" I.D 316 stainless steel tubing. Two 2100GP Motorola pressure transducers are connected to the U-arm by "T" junction Swagelock fittings.

Gas Flow Line

The GFL is connected to the U-arm by a "T" junction. Since the GFL is the mass spectrometer interface, capillary tubing reduces to molecular flow. Molecular flow is characterized as

$$c_{mp} = \sqrt{\frac{2kT}{m}} \qquad (4)$$

where k is Boltsmann's constant and T is the absolute temperature.

The GFL is made of 0.01" I.D. stainless steel capillary tubing.

Experimental

The first GCU prototype (GCU-1) was constructed. A 0.128" diameter pressure-regulated nozzle was placed 1" from the inlet of the probe. Inlet air pressure was varied and pressure measurements taken at inlet, P_1, and the throat, P_2 (see Figure 6). The output of the pressure transducers was conditioned and converted to voltage using LM741 op-amps. The voltages were measured with a hand- held multi-meter.

After the pressures were recorded, a flowmeter was inserted to measure volumetric flow through the U-arm. The flowmeter gave an output in standard cubic feet per hour. Given the pressure measurements, volumetric flow through the U-arm was calculated using equation 3 and compared with measurements (see Table 1).

The mach number at the inlet, M1, and the throat, M2, were calculated by substituting static pressures, P_1 and P_2 in equations 1 and 2. After P_t and A^* were eliminated from these equations, M1 and M2 were solved simultaneously. The stagnation pressure, P_t, was computed directly from equation 1.

Results and Discussion

Data collected from GCU-1 is shown in Table 1. The Mach number at the nozzle throat was plotted versus measured pressure ratio (see Figure 4). It can be seen that as the flow into the GCU was increased, the throat Mach number approached 1.0. This occurred for low inlet mach number (under 0.1). Since it is anticipated that inlet mach number will be around 0.5-1.0 for the actual rocket plume, the nozzle area ratio must be reduced.

The volumetric flow through the U-arm was predicted using equation 3 and measured using an in-line flow meter (see Figure 5). Flow in the expected direction occurred; however the predicted flow is much higher than the actual flow. This flow meter and its connection to the U-arm resulted in large losses, which were quantified in terms of a pressure drop across the flow meter. This pressure drop reduced the head available for flow, and a lower flow results with the flowmeter in the system. Therefore, the predicted flow values are more realistic for the actual U-arm than the measured values. The flow measurement does provide qualitative confirmation of the design.

The flow values in GCU-1 are much higher than the target design values. Since the qualitative design has been confirmed and since equation 3 has been validated for design purposes, a redesign to achieve the target flow rates will be relatively simple. In order to reduce flow through the U-arm, both the pressure drop across the U-arm and the cross-sectional area of the U-arm tubing need to be decreased.

Conclusions

The prototype, GCU-1, qualitatively verified the design concept. Pressure and flow measurements were taken to validate the design concept and generate preliminary design information for the next iteration.

Measurement of flow through the U-arm confirmed the venturi design and the assumption that Bernoulli's equations would allow design calculations to be made.

Since a low pressure differential produced high flow rates through the U-arm, it will be necessary to reduce the nozzle compression and the U-arm cross-sectional area.

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References

1. Shanks, R. B. and M.K. Hudson, "The Design and Control of a Labscale Hybrid Rocket Facility for Spectroscopy Studies." AIAA 94-3016 June 1994.

2. Tejwani, Gopal. et al. "Space Shuttle Main Engine Exhaust Plume Spectroscopy" Spectropscopy 11(9) (1996): 31-43.

3. John, E.A. Gas Dynamics. Boston: Allyn and Bacon, Inc., 1984.

4. Teague, M. Warfield. Et al. "UV-VIS Absorption as a Diagnostic for NO Rocket Plumes." International Journal of Turbo and Jet Engines, 13, (1996) 211-215.

5. Bertin, John J. Engineering Fluid Mechanics. New Jersey: Prentice-Hall, Inc., 1984.

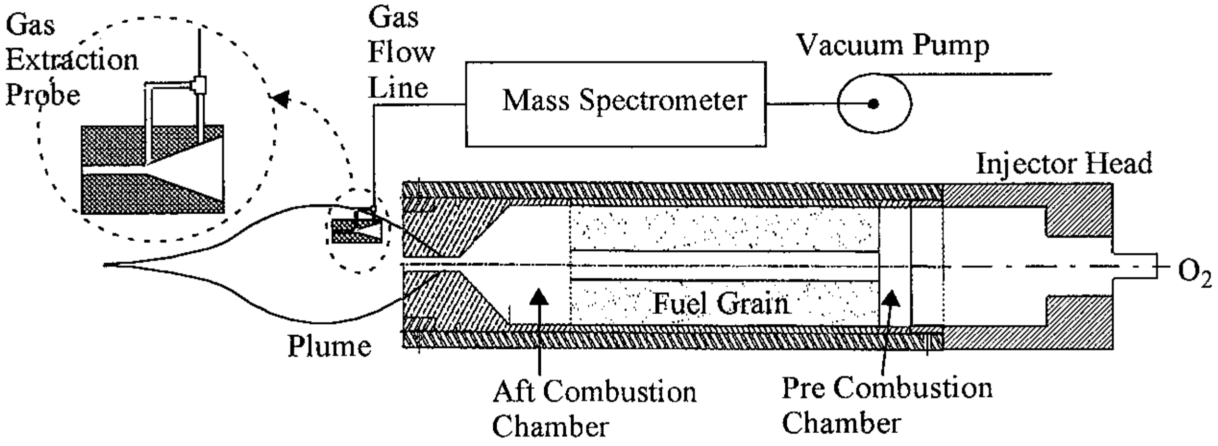

FIGURE 1: Hybrid rocket motor and gas extraction system

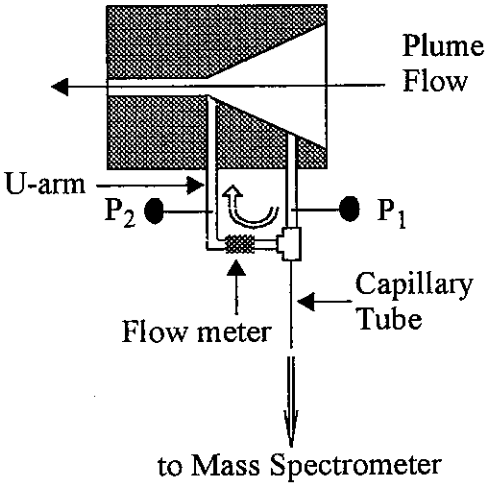

FIGURE 2: Gas Collection Unit (GCU)

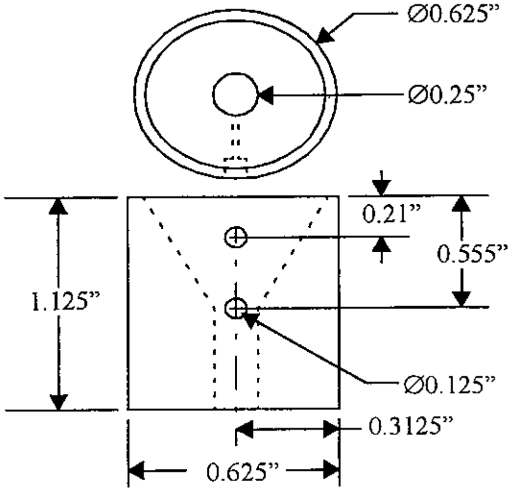

FIGURE 3: Gas Collection Probe (GCP)

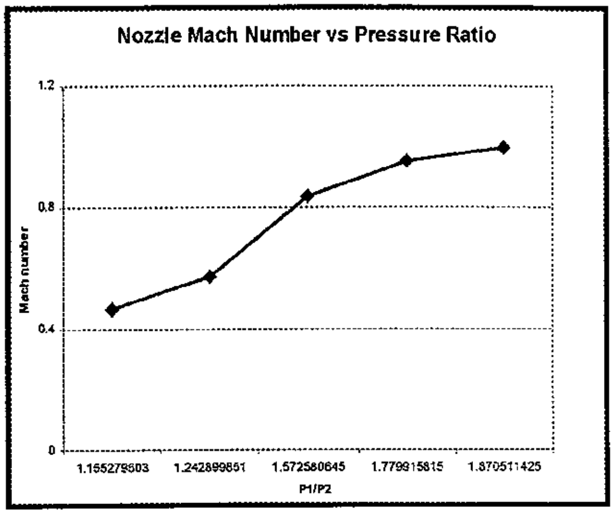

FIGURE 4: Mach number at throat versus pressure ratio

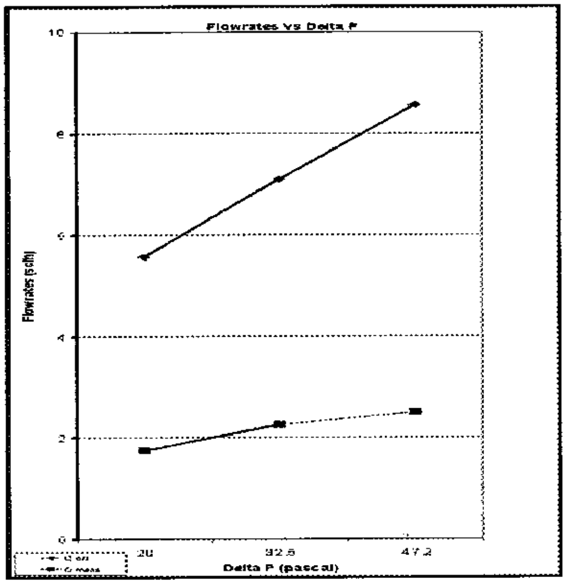

FIGURE 5: Volumetric flow rate through U-arm

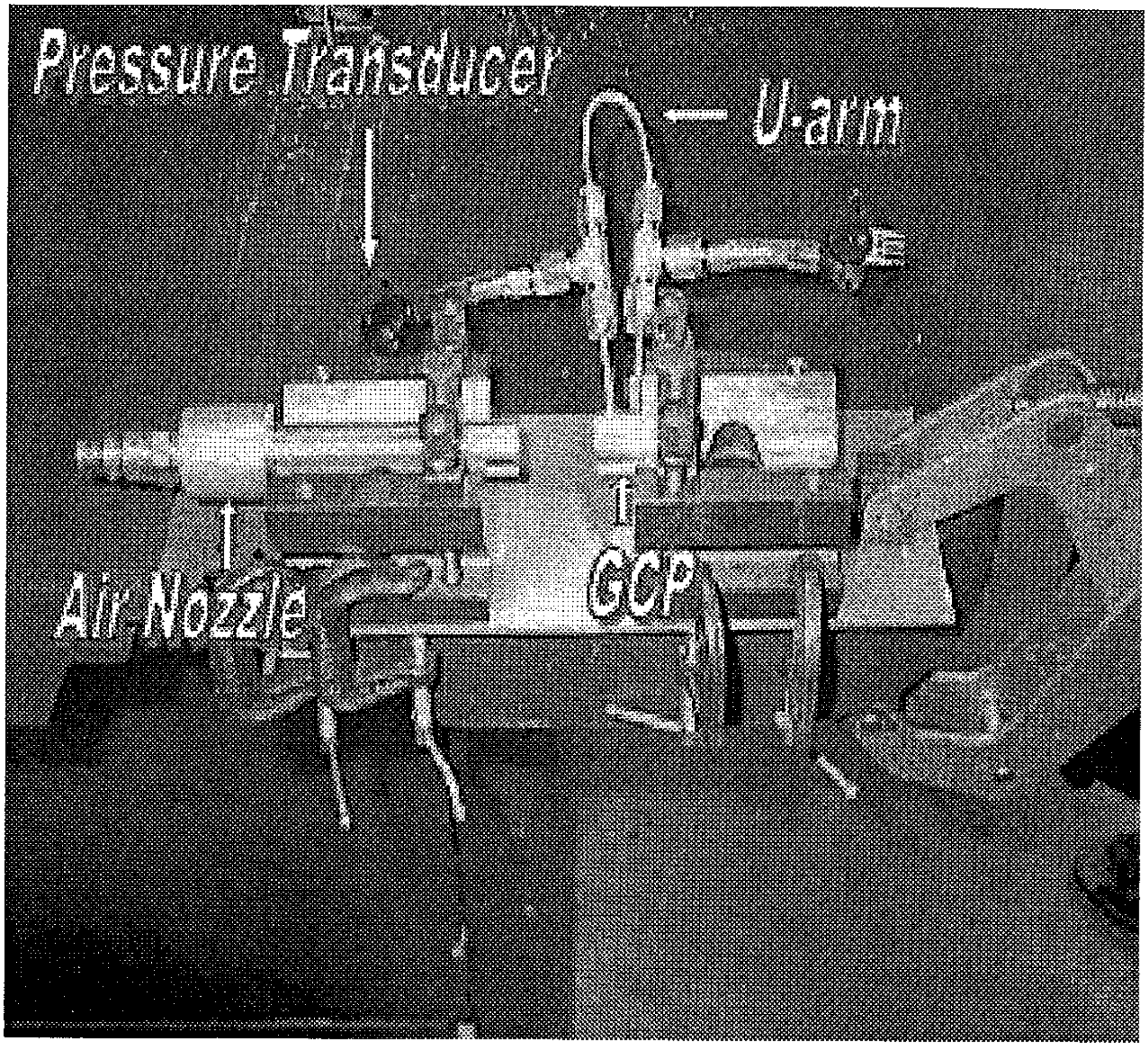

FIGURE 6: Gas Collection Unit (GCU) Experimental Set-up

M_1	M_2	P_t (Pa)	P_1 (Pa)	P_2 (Pa)	ΔP (Pa)	Calc. Flow (scfh)	Meas. Flow (scfh)
0.0672	0.4639	149.3	148.8	128.8	20	5.573	1.75
0.0775	0.5717	167	166.3	133.8	32.5	7.104	2.25
0.0926	0.8368	235.4	187.3	140.1	47.2	8.561	2.5
0.095	0.9519	297.9	234	148.8	85.2	11.503	Max
0.095	0.9952	346	296	166.3	129.7	14.192	Max

Table 1: Data for GCU-1