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Pressure and Flow Validation of a Second Generation Gas Extraction Probe for a Hybrid Rocket Gas Extraction System

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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 flow-rate and pressure, the GES extracts gases from the hybrid rocket plume and transports them to a mass spectrometer. This paper describes 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 two venturi-type GEP, converging and converging-diverging. The probe was tested with air to verify design assumptions. Flow rate through the U-arm and pressures for each probe were measured and compared.

Introduction

The University of Arkansas at Little Rock's (UALR) labscale hybrid rocket (Shanks and Hudson, 1994) facility is shown schematically in Fig. 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 complexity and higher propellant density). Hybrids use solid fuels, such as hydroxl-terminated polybutadiene (HTPB) and methyl methacrylate, and they burn at high temperatures. These two factors may lead to undesirable exhaust constituents (Meadors et al., 2000).

NASA's John C. Stennis Space Center (SSC) has done extensive research in the area of plume spectroscopy (Tejwani, et al., 1996). One of SSC's 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

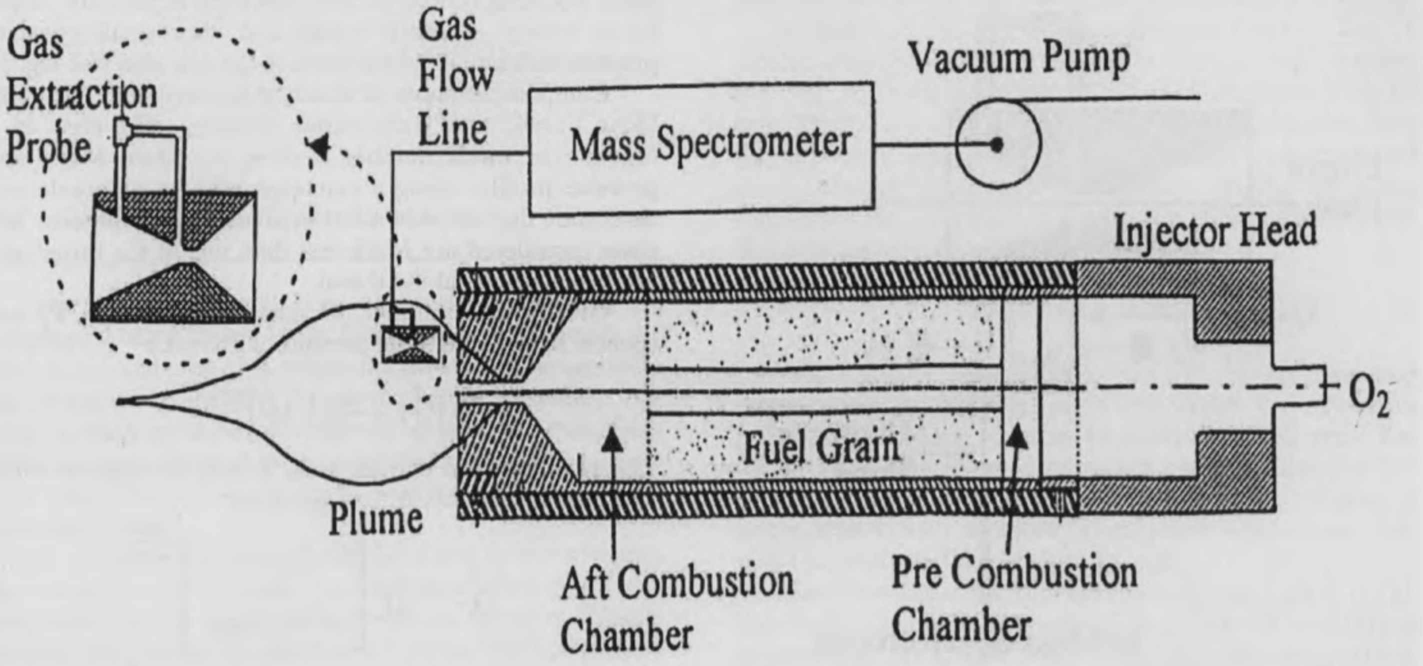

Fig. 1. Hybrid Rocket Motor and Gas Extraction System.

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 (Tejwani et al., 1996). 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 long term goal for this project is to continuously extract gases from the hybrid rocket plume and transport them to a mass spectrometer (see Fig. 1). The probe will be inserted in the plume so as to minimally disturb the flow pattern. The pressure differential between the U-arm inlet and the nozzle exit will drive a secondary metered flow through the probe's U-arm. A "T" junction removes plume constituents in small amounts and transports via capillary tubing and transports them to a mass spectrometer (see Fig. 2). This paper focuses on the design of the gas extraction probe (GEP).

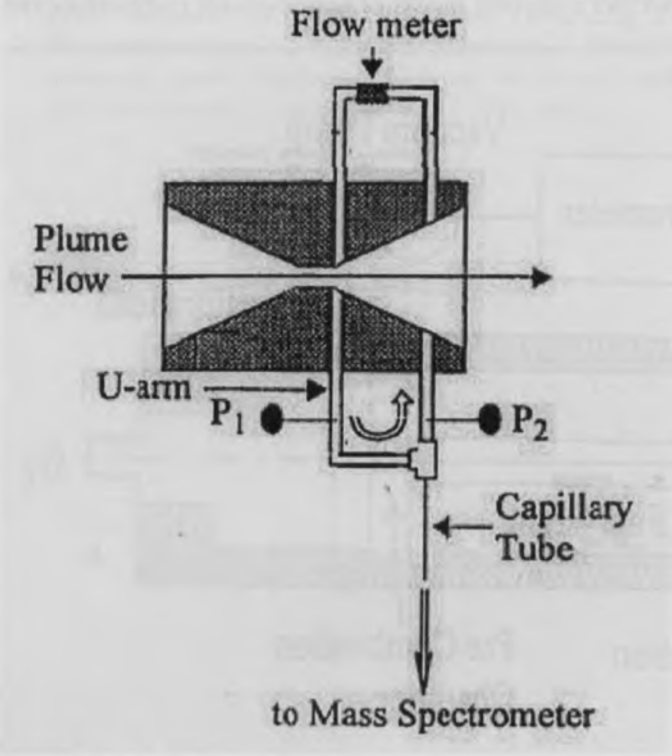

Fig. 2. Gas Collection System.

Materials and Methods

Gas Extraction System Design.--The gas extraction system consists of a gas collection unit (GCU), a gas flow line (GFL), and a Finnegan 5100B mass spectrometer (see Fig. 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 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 (Teague, et al., 1996), 30 psi (206.8 kPa) stagnation pressure, and a Mach number varying between 0.5-1.5. Mass spectrometer interface requirements are 20-25mL/min inlet flow rate and 0.19-.09 psi (1.3-.66 kPa) vacuum pressure.

Gas Collection Unit 2.--In GCU-1 a low variable pressure differential produced high flow rates through the U-arm. To achieve target flow rates through the U-arm (Meadors and Wright, 1999), a second GCU is designed with a new probe that provides a small constant pressure differential. The second GCU employs the same venturi function as GCU-1 (see Fig. 2).

Gas Collection Probe 2.--Using one-dimensional, isentropic, compressible flow assumptions (Potter and Foss, 1982; John, 1984), gas collection probe-2 (GCP-2) is designed to achieve ideal mach numbers, pressure, and flow rates. The ideal conditions will yield a stable pressure output for a variety of Mach inputs and very small constant pressure differential with a shock in the exit area (see Fig. 3).

Computer analysis of standard gas dynamic equations (John, 1984) that demonstrate pressure and area as a function of Mach number is done to create Mach and pressure profiles along a convergent-divergent nozzle and determine the best area ratios to meet ideal conditions. Two cases considered are Mach less than one at the throat and Mach equals one at the throat.

Given Mach number, M, stagnation pressure, P_t, and specific heat, γ, the static pressure is given by

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

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

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

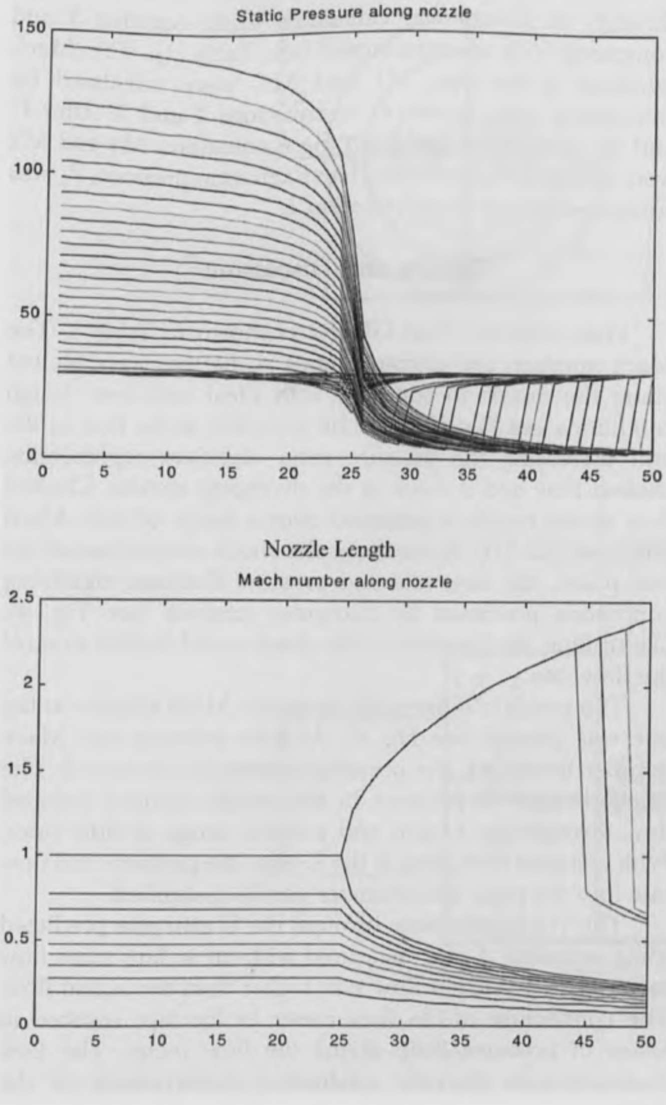

Fig. 3. Ideal Mach and Pressure Conditions.

The area ratios and pressures were determined by equations 1 and 2 (John, 1984). Static and back pressures are used to calculate the area before the throat. The areas up to the shock are calculated by varying static pressure. The static to back pressure ratio is used to solve the exit plane mach number which is used to calculate exit area to throat area ratio. Once the shock is reached the converging section does not change.

To calculate the second case the shock is moved along the nozzle from the throat to exit plane. Since isentropic properties do not apply across a shock, given the Mach number, M1, before the shock and γ (John, 1984), the Mach number after the shock is given by

$$M2 = \sqrt{\frac{M1^2 + \frac{2}{\gamma - 1}}{\frac{2\gamma}{\gamma - 1} M1^2 - 1}} \ . \qquad (3)$$

Given M1 the stagnation pressures across the shock are characterized by

$$\frac{P_{t2}}{P_{t1}} = \left[\frac{\frac{\gamma + 1}{2} M_1^2}{1 + \frac{\gamma - 1}{2} M_1^2}\right]^{\gamma/\gamma\text{-}1} \left[\frac{1}{\frac{2\gamma}{\gamma + 1} M_1^2 - \frac{\gamma - 1}{\gamma + 1}}\right]^{1/\gamma\text{-}1} . \qquad (4)$$

The backpressure, inlet, exit, and throat area are factors considered and varied in analysis. Inlet and throat areas were selected and the exit area varied. The Mach number and static pressures were plotted along the nozzle. The inlet area was then varied to see its effect on the exit conditions. Finally, the throat area was varied to gain the best possible inlet and exit conditions. The best computed area ratios are inlet to throat of 1.15 and exit to throat of 2 (see Fig. 4).

GCP-2 is designed with variable inlet Mach numbers 0.2-1.0 and a stagnation pressure of 30 psi (206.8 kPa). GCP-2 is made of aluminum with an inlet diameter of 2.64 cm, a throat diameter of 1.09 cm, and an exit diameter of 3.56 cm, yielding an inlet to throat ratio of 5.67 and an exit to throat ratio of 10. For design purposes these ratios are twice the ideal ratios. The probe has two sets of holes drilled and tapped with 1/16 NPT in the diverging section. Two holes are on each side of the probe 1.4 cm apart. One set of the holes is 0.51 cm from the throat and the other is 1.91 cm from the exit plane. The probe is 6.35 cm long (see Fig. 5).

U-arm.--GCU-2 is designed with two U-arms. The U-arm is designed similar to the old carburetor venturi meter (see Fig. 2). Gases enter the probe and flow through the U-arm (Meadors and Wright, 1999). Assuming frictionless flow through the U-arm, the volumetric flowrate, Q, is expressed as a function of pressure difference, P_1-P_2, by using Bernoulli's equation (Bertin, 1984). The volumetric flow rate through the arm is characterized by

$$Q = A\sqrt{\frac{2(P_1 - P_2)}{\rho}} \ . \qquad (5)$$

One U-arm is made of 0.123 cm I.D. 316 stainless steel tubing and instrumented with two 2100 GP Motorola pressure transducers to measure pressure at the taps. The pressure transducers are connected to the U-arm by "T" junction Swage-lock fittings. The second U-arm is instrumented with a 43600 Honeywell inline mass flow meter to measure flowrate (see Fig. 2).

Gas Flow Line.--The gas flow line is connected to the U-arm with the pressure transducers only. The GFL is connected to the U-arm by a "T" junction. Since the GFL is the mass spectrometer interface, capillary tubing reduces to

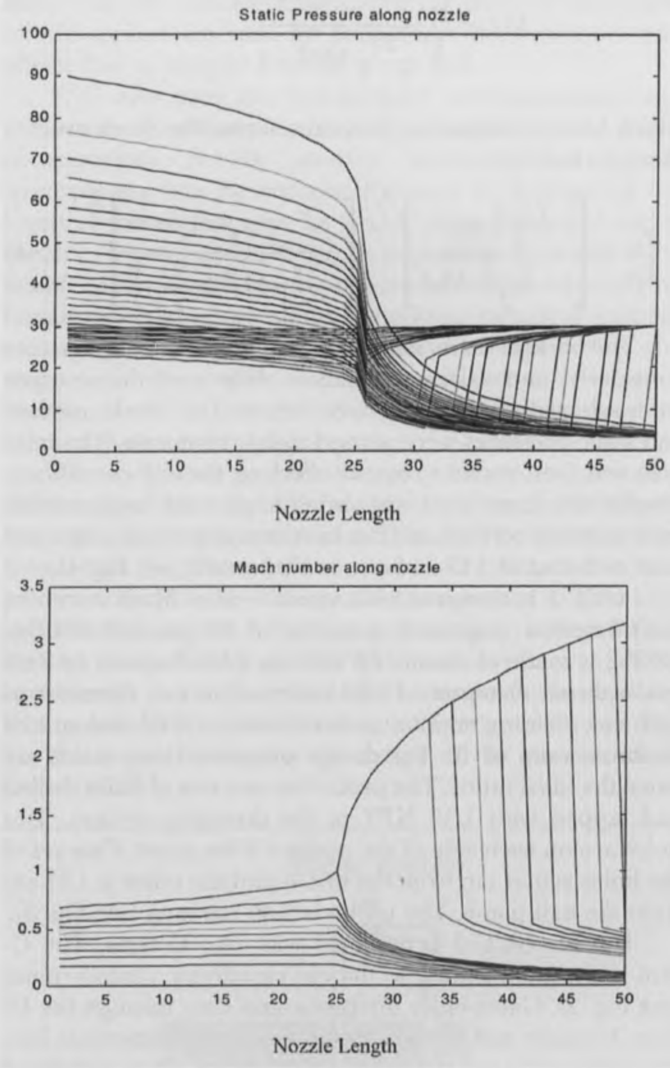

Fig. 4. Best Mach and Pressure Conditions.

molecular flow. Molecular flow is characterized as

$$c_{mp} = \sqrt{\frac{2kT}{m}}\,, \qquad (6)$$

where k is Boltsmann's constant and T is the absolute temperature. The GFL is made of 0.25 cm I.D. stainless steel capillary tubing.

Experimental.--GCU-2 was constructed. A 0.33cm diameter pressure-regulated nozzle was placed 2.54 cm from the inlet of the probe. While inlet air pressure was varied, pressure and flow measurements were taken at the taps (see Fig. 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 multimeter.

Given the pressure measurements, volumetric flow through the U-arm was calculated using equation 5 and compared with measurements (see Table 1). The Mach numbers at the taps, M1 and M2, were calculated by substituting static pressures 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-2 is shown in Table 1. The Mach numbers and pressure ratios at the taps were plotted along the nozzle to compare with ideal and best design conditions (see Fig. 7). It can be seen that as the flow in the unit increased, the pressure ratio stabilizes representing choked flow and a shock in the diverging section. Choked flow in the nozzle is achieved over a range of inlet Mach numbers (0.2-1.0). However, as the shock moves toward the exit plane, the flow rate and pressure fluctuate signifying conditions predicted by computer analysis (see Fig. 4). Controlling the location of the shock could further control the flow rate.

The pressure differential versus the Mach number at tap one was plotted (see Fig. 8). As inlet pressure and Mach number increased, the pressure differential decreased. The small changes in pressure in the nozzle produce reduced flow through the U-arm and a stable range of flow rates. With constant flow rates in the U-arm, the pressure and flow rate into the mass spectrometer can be controlled.

The volumetric flow through the U-arm was predicted using equation 3 and measured with an in-line mass flow meter. The predicted flow was higher than the actual flow. The connection of the flow meter to the taps resulted in losses of pressure drop across the flow meter. The flow measurements provide qualitative confirmation of the design.

Conclusions

The prototype, GCU-2, 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. GCP-2 verified that with a shock in the U-arm, constant flow and pressure into the mass spectrometer or other measuring devices can be achieved over a range of inlet pressures. A high and low flow probe can be designed to transport gases from the rocket to the mass spectrometer. Pressure measurements at the GFL should be taken to confirm flow rate into the mass spectrometer.

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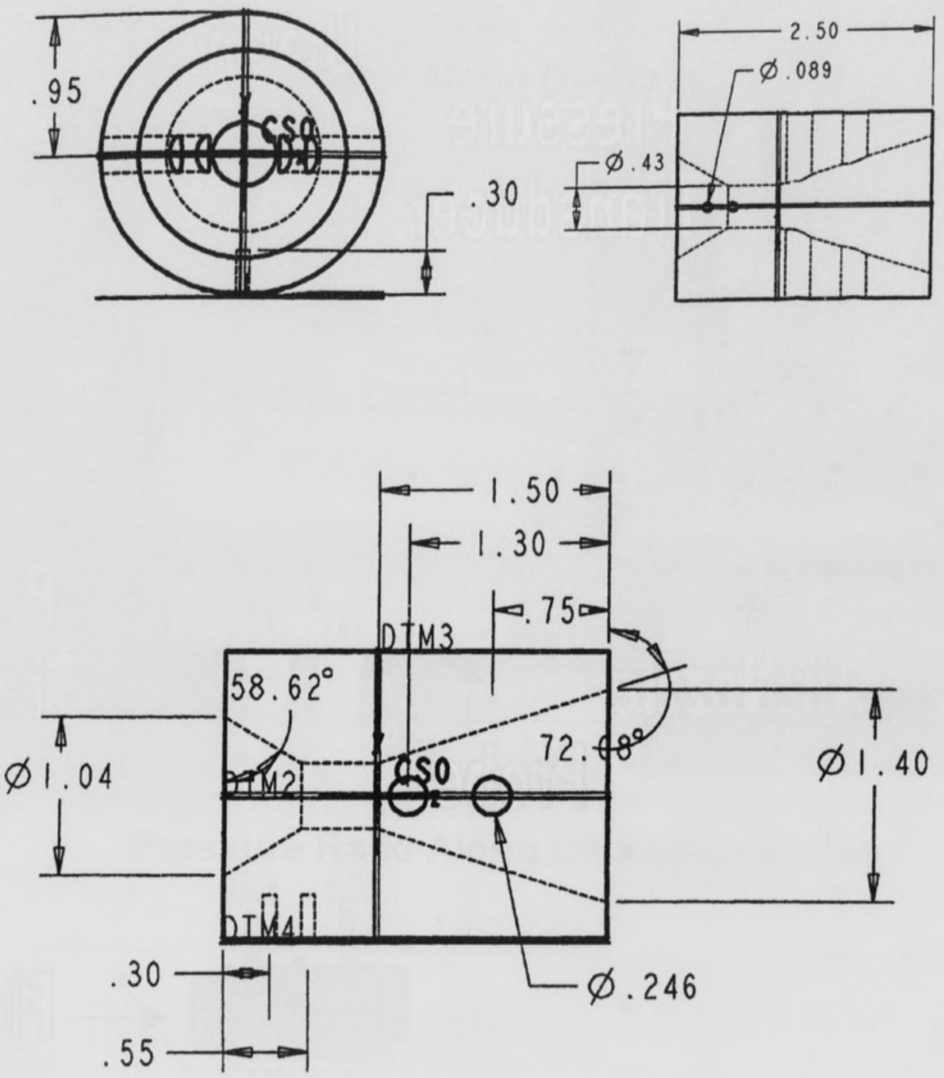

Fig. 5. Gas Collection Probe-2.

collaboration and assistance in the design of the GCU. We would like to thank Armand Tomany for fabrication of the prototype and for assistance in setting up the flow experiments. This work is supported by the Arkansas Space Grant Consortium through Collaborative Research Project grant and student fellowship. This work is also supported by NASA through a GSRP Fellowship.

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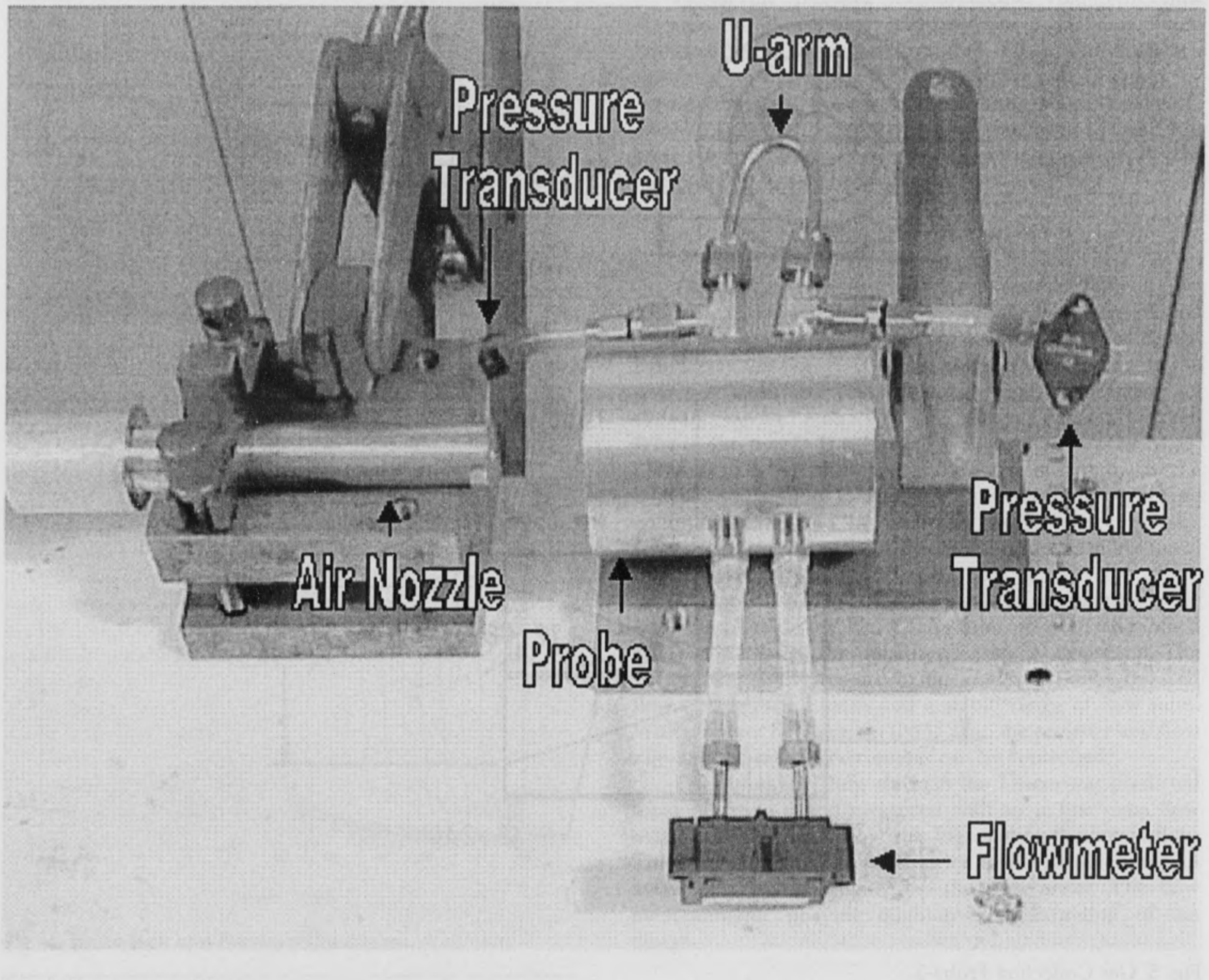

Fig. 6. Experimental Setup

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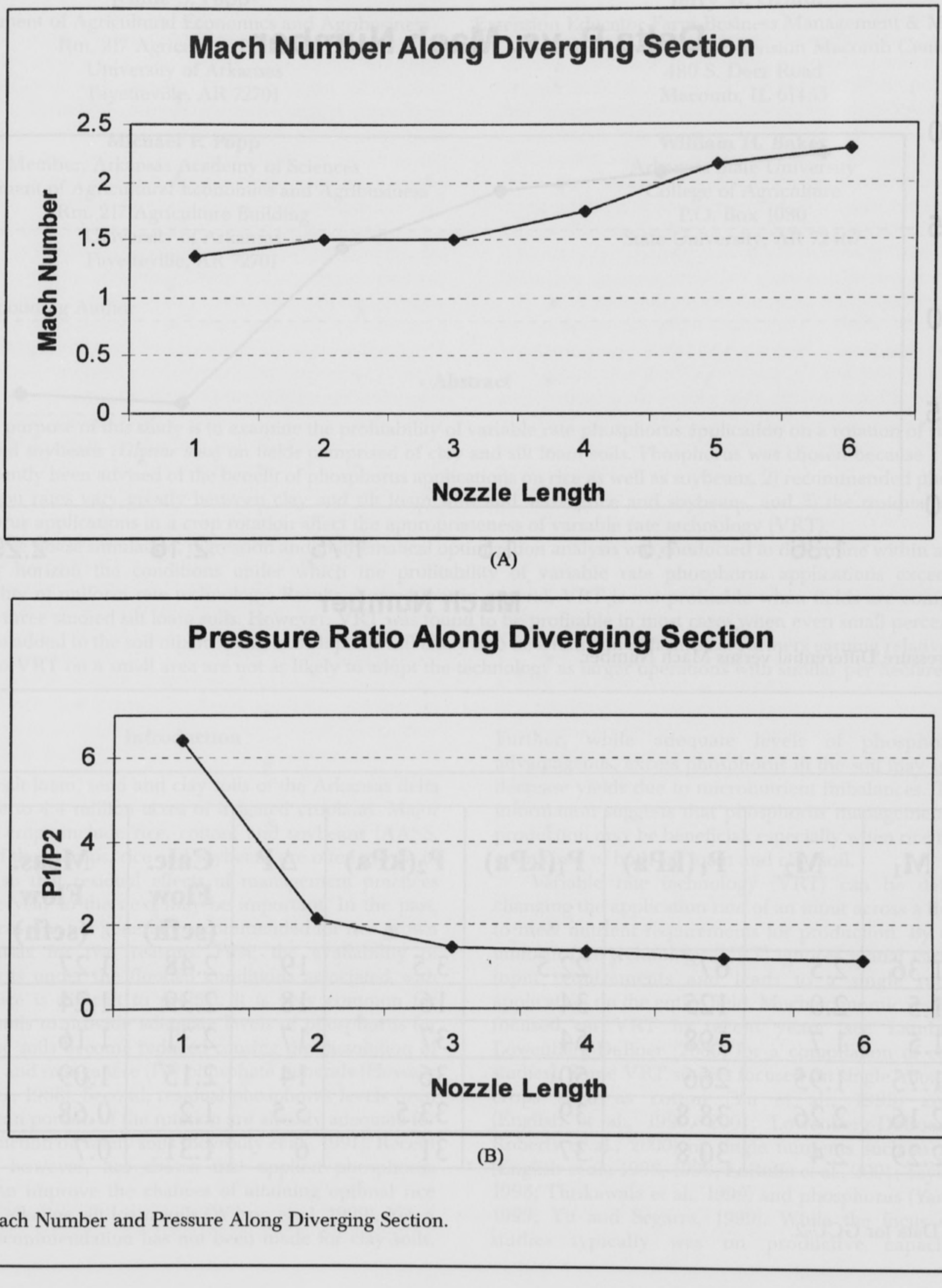

(A)

(B)

Fig. 7. Mach Number and Pressure Along Diverging Section.

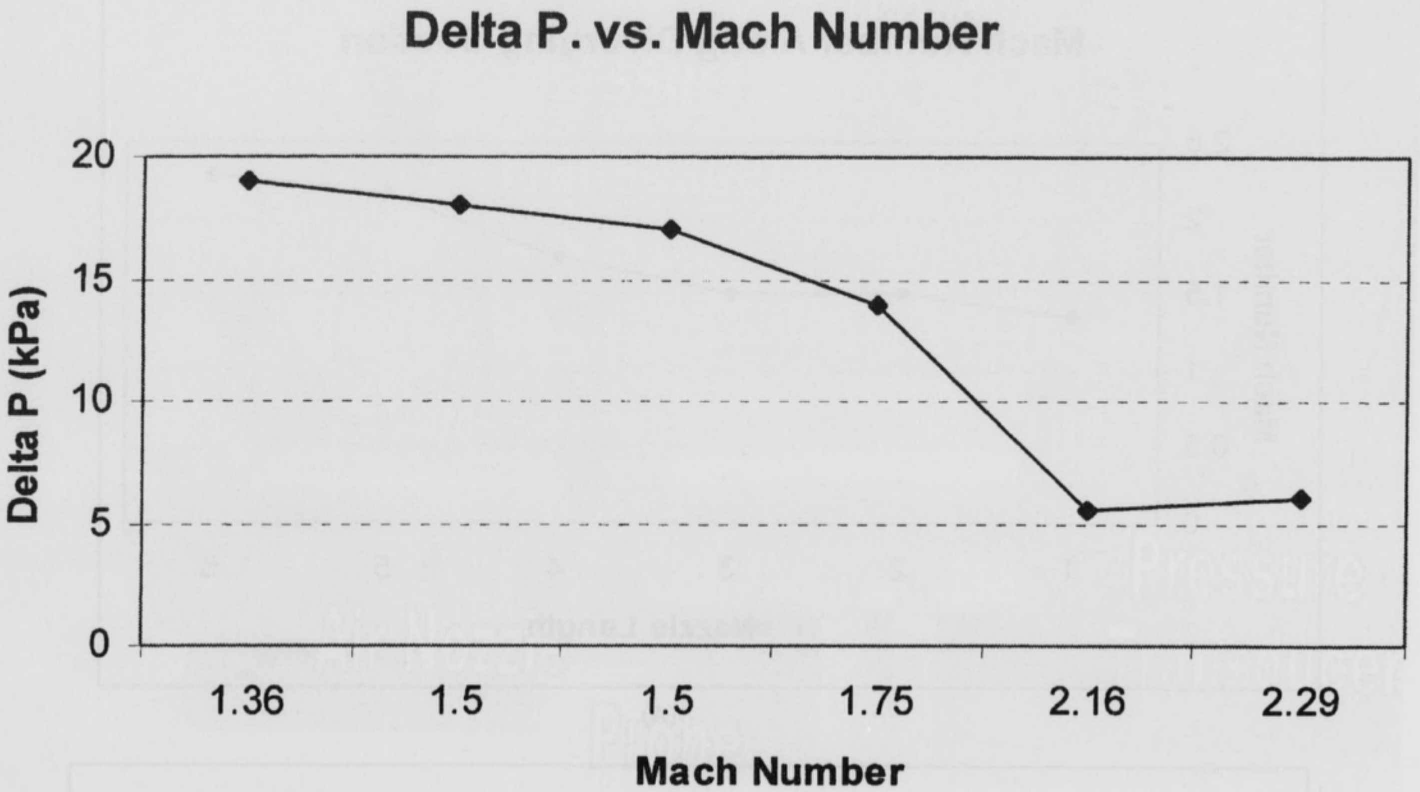

Fig. 8. Pressure Differential versus Mach Number.

M_1	M_2	P_t (kPa)	P_1(kPa)	P_2(kPa)	ΔP	Calc. Flow (scfh)	Meas. Flow (scfh)
1.36	2.5	67	22.5	3.5	19	2.48	1.27
1.5	2.0	125	34	16	18	2.39	1.24
1.5	1.7	198	54	37	17	2.31	1.16
1.75	1.95	266	50	36	14	2.15	1.09
2.16	2.26	38.8	39	33.5	5.5	1.2	0.68
2.29	2.4	30.8	37	31	6	1.31	0.7

Table 1. Data for GCU-2.