APPLICATION OF A VORTEX SHEDDING FLOWMETER TO THE WIDE RANGE MEASUREMENT OF HIGH TEMPERATURE GAS FLOW+

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A single flowmeter was required for helium gas measurement in a Gas Cooled Fast Breeder Reactor loss of coolant simulator. Volumetric flow accuracy of ± 1.0% of reading was required over the Reynolds Number range 6 X 10^3 to 1 X 10^6 at flowing pressures from 0.2 to 9 MPa (29 to 1305 psia) at 350°C (660°F) flowing temperature. Because of its inherrent accuracy and rangeability, a vortex shedding flowmeter was selected and specially modified to provide for a remoted thermal sensor. Experiments were conducted to determine the relationship between signal attenuation and sensor remoting geometry, as well as the relationship between gas flow parameters and remoted thermal sensor signal for both compressed air and helium gas. Based upon the results of these experiments, the sensor remoting geometry was optimized for this application. The resultant volumetric flow rangeability was 155:1. The associated temperature increase at the sensor position was 9°C above ambient (25°F) at a flowing temperature of 350°C. The volumetric flow accuracy was measured over the entire 155:1 flow range at parametric values of flowing density. A volumetric flow accuracy of ± ___ % of reading was demonstrated.

+Research sponsored by the U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

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INTRODUCTION

A single flowmeter was required for recirculating helium gas flow measurement over a wide range of conditions in a Gas Cooled Fast Breeder Reactor loss of coolant simulator, the ORNL Core Flow Test Loop (CFTL). Volumetric flow accuracy of $\pm$ 1.0% of reading was required over the Reynolds Number range 6 X 10^3 to 1 X 10^6 at flowing pressures from 0.2 to 9 MPa (29 to 1305 psia) at 350°C (660°F) in 4 inch and 6 inch schedule 80 pipe. In addition, it was required that a fast time response and maintenance of accuracy during large flow and pressure transients be provided. Due to the characteristics of the helium gas circulators, a low pressure drop across the flowmeter was required. Also, it was necessary to maintain the helium gas free of contaminants to high purity levels; thus, the flowmeter provided could not be a source of contaminants of any kind. An extensive survey and several studies were carried out to identify candidate flowmeters for this application[1]. As an outgrowth of these studies, it was decided to modify a commercial vortex shedding flowmeter (VSFM) to fulfill the CFTL requirements. For this purpose, unassembled commercial VSFM components were obtained for incorporation in a modified assembly.

DESIGN APPROACH

Two flowmeter characteristics determine the rangeability of a VSFM in a given application, namely: the range of linearity of the meter factor; and the sensitivity of the meter over the required range of flowing conditions. The inherrent nominal linearity of a VSFM can be 0.5%1.0% of reading over a Reynolds Number range from 10^4 to >10^6.[2] Therefore, in this application, the primary problem in achieving wide rangeability is in achieving adequate sensitivity over this Reynolds Number range at all flowing densities, particularily at low density, low flow conditions.

A self-heated thermistor was chosen as a vortex shedding sensor because it provides high sensitivity over the wide range of flowing conditions in this application. A commercial thermal sensor with a single ported cap was selected on the basis of its signal/noise ratio and frequency response.

However, its maximum operating temperature limit is nominally 200°C. Therefore, it was required to remote the thermal sensor away from the high temperture gas flow by the use of pressure taps routed to a lower ambient temperature region. Figure 1 shows the features of the VSFM design which was selected.

The assembly consists of a flow element (bluff body), pressure tap tubing extending from each side of the bluff body to a remote sensor block, a single-ported thermal sensor assembly, and signal conditioner. The bluff body is permanently mounted in the metering tube with precision dowel pin alignment. The remoting tubing transmits the pressure pulse associated with each shed vortex to the remoted sensor. The sensor block has integral shut-off valves that permit sensor removal without apening the flow system to atmospheric pressure. The path from the bluff body through the sensor block and valves is designed for minimum flow noise.

The entire assembly, including meter body, remote sensor mounting block, and remoting tubing are stainless steel. Since there is negligible net gas flow through the tubing loop from one side of the bluff body to the other, heat transfer from the metered gas flow to the remoted sensor is limited to conduction through the tubing and radiation from the pipe wall, which is covered with 2 inches of KAO insulation. Given this configuration, the thrust of the problem was to measure the signal attenuation as a function of remoting geometry, and then to optimize this geometry for signal and signal/noise ratio.

SENSITIVITY CONSIDERATIONS

In the remoted sensor design, there are three factors which determine sensitivity, namely:

- Amplitude of vortex-generated pressure pulses as a function of flowing conditions
- Thermal response curve of the sensor assembly
- Signal pressure pulse, attenuation associated with the remoting geometry

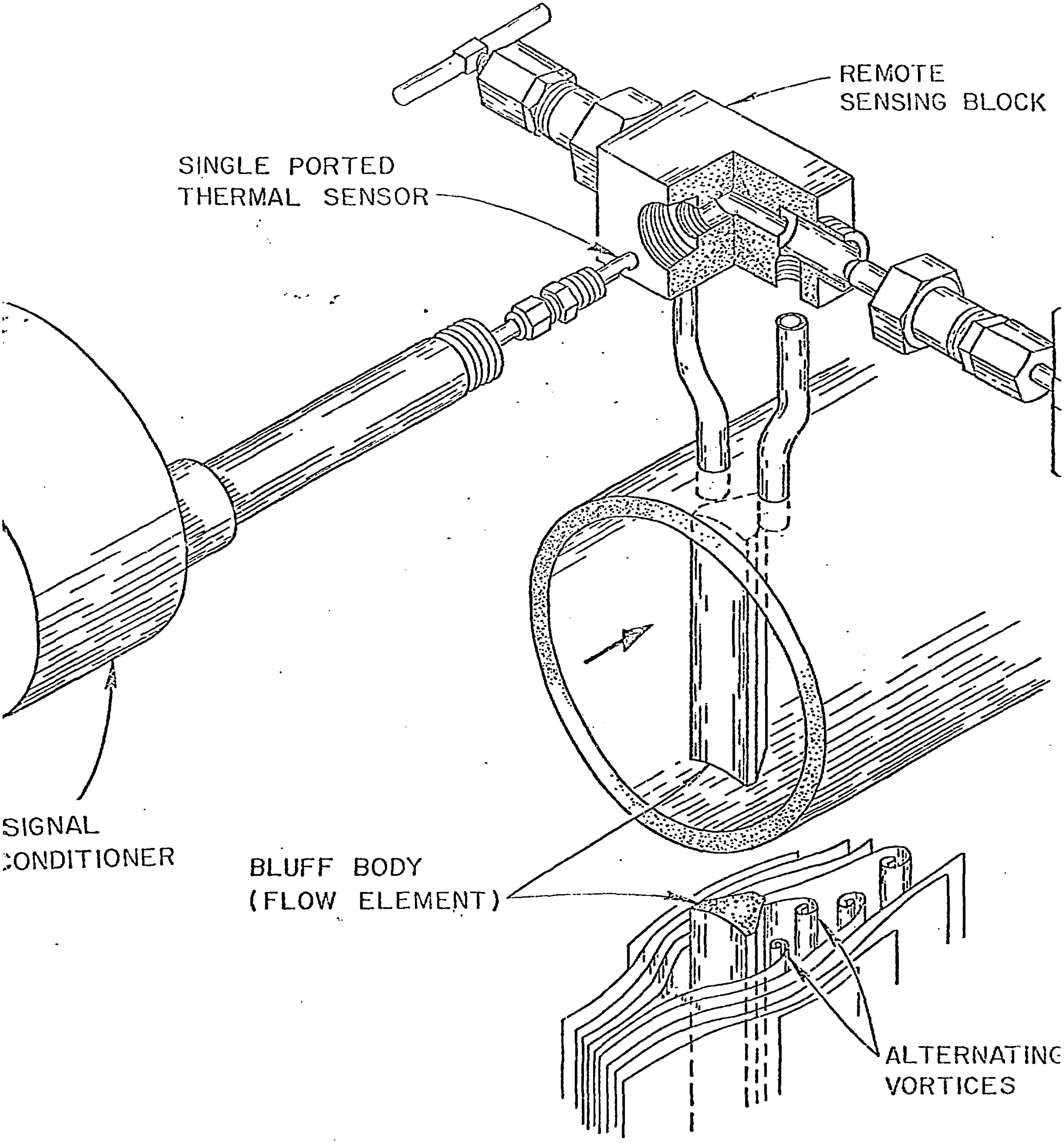

Figure 1. Modified VSFM

Variation of the amplitude of vortex-generated pressure pulses with flowing conditions is complex. To first order, the amplitude is proportional to ρq^2, where ρ is the flowing density and q is volumetric flow rate.[3] The amplitude is alos an increasing function of the meter diameter. Commercial VSFMs with remoted sensors have been unavailable in meter sizes under 8 inch, due largely to this effect on sensitivity.

The shed vortex transmits a pressure pulse through the remoting geometry to the thermal sensor assembly. The response of the sensor assembly depends upon the self-heated temperature, the geometry and specific heat capacity of the sensor portion, and the film coefficient of the gas at the sensor surface.[4]

Analysis of the pressure pulse attenuation of the remoting geometry is complex over the range of flowing conditions in this application. Likewise, the thermal response of the sensor assembly over the entire range would be difficult to satisfactorily predict analytically. Therefore, these factors and their interrelationship which determine meter sensitivity were investigated experimentally.

FLOW TESTING OF REMOTED SENSOR DESIGN

A number of measurements were required over a wide range of flow, density, and temperature conditions in order to empirically establish the signal/remoting geometry/flow condition relationships that would enable the optimization of the sensitivity of the modified VSFM. The following relationships required investigation, namely:

- Variation of vortex signal as a function of flowing conditions
- Attenuation of vortex signal output as a function of remoting geometry
- Remoted sensor signal/noise ratio as a function of remoting geometry and flowing conditions
- Temperature increase above ambient of the remoted sensor as a function of flowing conditions

A closed loop helium gas system was unavailable during the course of this work. Therefore, the entire series of tests on the modified VSFM were conducted in an open loop system schematically shown in Figure 2. In order to conserve helium, the bulk of the measurements were carried out on compressed air flow. Once the basic relationships were determined on compressed air flow, final measurements and optimization of sensor remoting geometry were carried out on helium gas flow.

The test loop consisted of three prinicpal portions: a helium supply branch for introduction of helium from a high pressure tube trailer; an orifice metering run for the reference measurement of both compressed air and helium flow; and a VSFM metering run downstream of a gas heater. Flow, pressure, and flowing temperature could be varied at the VSFM metering run over the ranges given in Table 1.

Table 1 - Test Loop Flowing Conditions

Fluids	Compressed Air Helium Gas
Flowing Density	0.6 kg/m^3 - 8.5 kg/m^3 (3.7 x 10^{-2} lb/ft^3 - 5.4 x 10^{-1} lb/ft^3)
Reynolds Number	6 x 10^3 - 1.1 x 10^6
Flowing Pressure	0.1 - 0.79 MPa (15 PSIA - 115 PSIA)
Flowing Temperature	24 - 290°C

SIGNAL CONDITIONER THRESHOLD RESPONSE

In order to determine the minimum sensor signal required to produce a reliable square wave output, it was necessary to measure the threshold response of the signal conditioner over the vortex shedding frequency range (0-400 Hz). The threshold response is defined as the minimum peak-to-peak input voltage that will reliably trigger a square wave output.

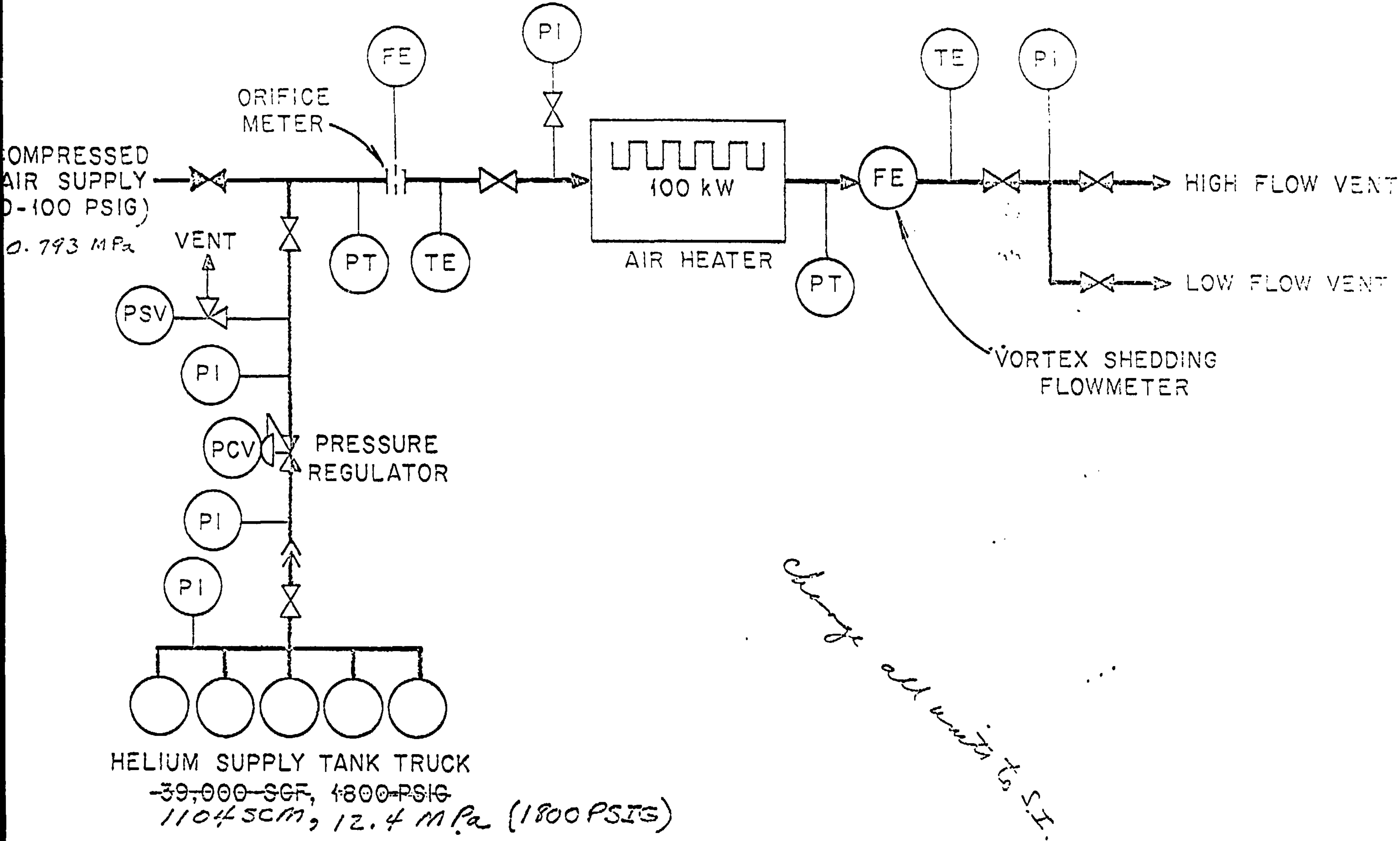

Figure 2. Test Loop Used For Remoted Sensor Signal Measurements

These measurements were made using the system shown in Figure 3. The VSFM thermal sensor and electronics were removed from the meter body, and these response tests were conducted in still air. A precision signal generator was used to simulate the sinusoidal input signal across the sensor.

The results of these response tests are presented in Figure 4. The applied voltage across the sensor, V_a, was optimized for the impedance of the sensor to produce minimum threshold. A 60 Hz noise level of 300 V was observed over the entire frequency range. This is due to the ripple from the VSFM power supply.

Based upon these results, it was concluded that the nominal input threshold of the signal conditioner is 1.0 mV peak-to-peak, which represents a nominal signal/noise ratio of 3:1. Therefore, under all flowing conditions a minimum sensor signal of 1.0 mV p-p must be achieved.

REMOTED SENSOR SIGNAL PERFORMANCE

During all signal performance measurements, both the sensor signal and the square wave output of the signal conditioner were observed simultaneously on a dual-channel storage oscilloscope. Typical oscilloscope traces for low flow and high flow conditions are shown in Figures 5 and 6. Each cycle corresponds to a shed vortex. Considerable variation occurs in the peak-to-peak sensor signal at a given flowing condition. This variation can be as much as a factor of 5:1.

To ensure reliable detection of shed vortices, the sensor signal must be maintained at a value greater than the threshold of the signal conditioner. Therefore, all data in this section is presented in terms of the minimum peak-to-peak sensor signal, V_s.

The dependence of V_s upon remoting tubing geometry was measured. At constant volumetric flow, density, and tubing diameter, the tubing length was incrementally varied. A log-log plot of V_s versus tubing length, ℓ, is presented in Figure 7. From the slope of this curve it was determined that V_s varies as $1/\sqrt{\ell}$. Physical limitations in connecting the tubing and sensor

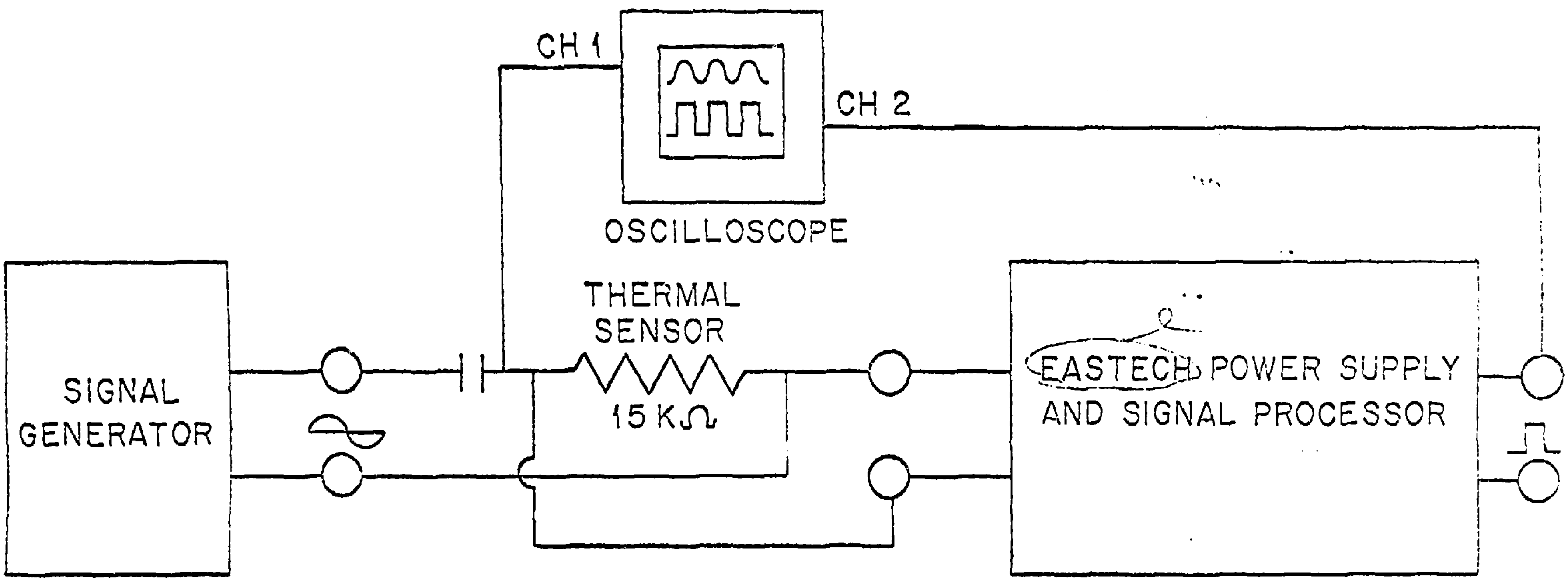

Figure 3. Block Diagram of System for Measurement of Signal Conditioning Electronics Threshold Response

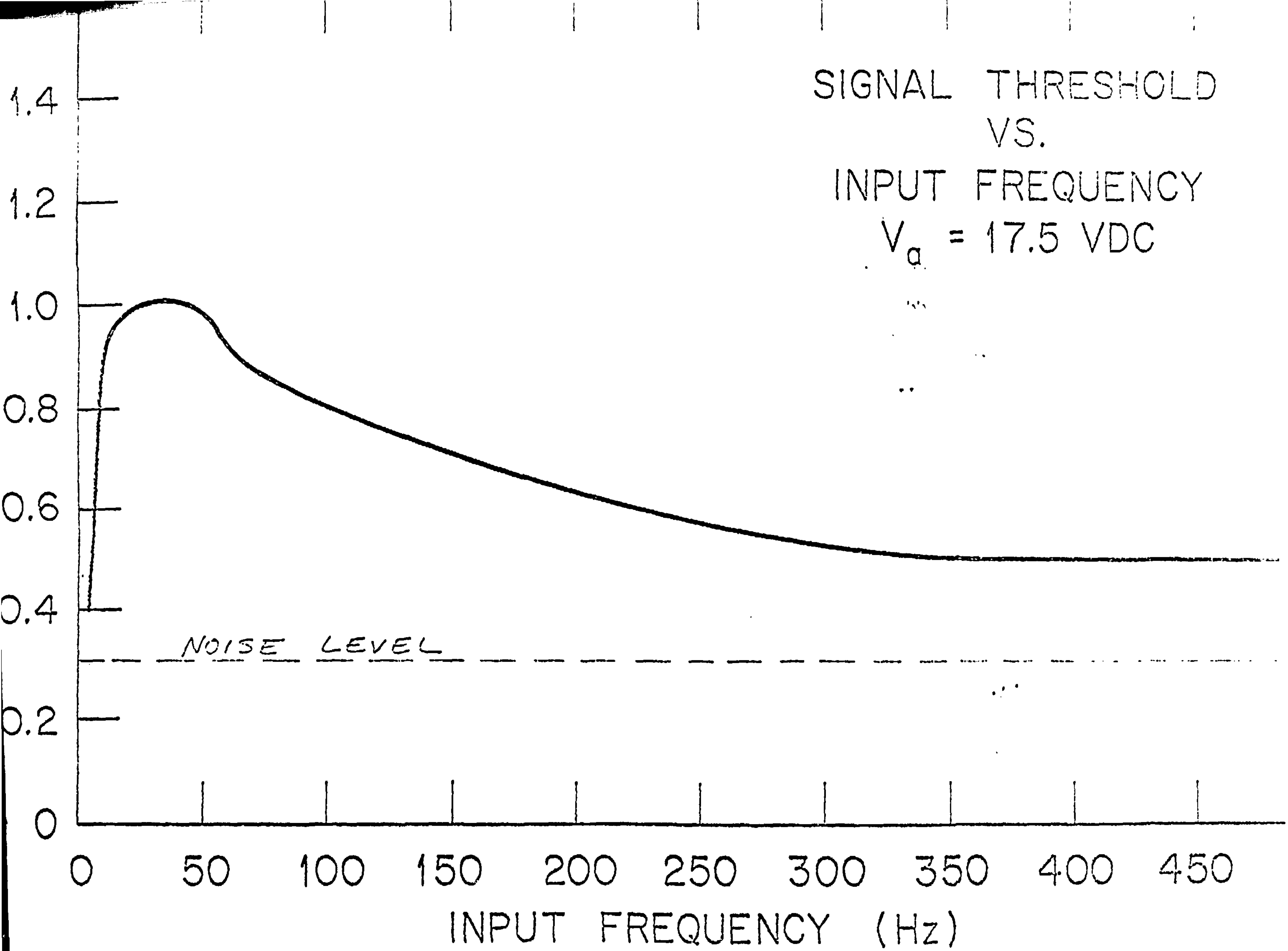

Figure 4. Signal Conditioning Electronics Threshold Response

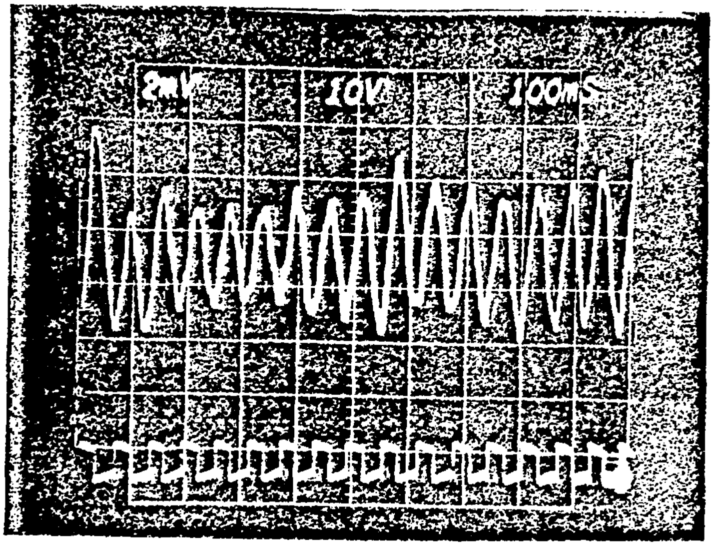

Figure 5. Oscilloscope Trace of Sensor Output (Channel 1) and Signal Conditioner Output (Channel 2) at Low Flow (Vortex Shedding Rate = 15 Hz_

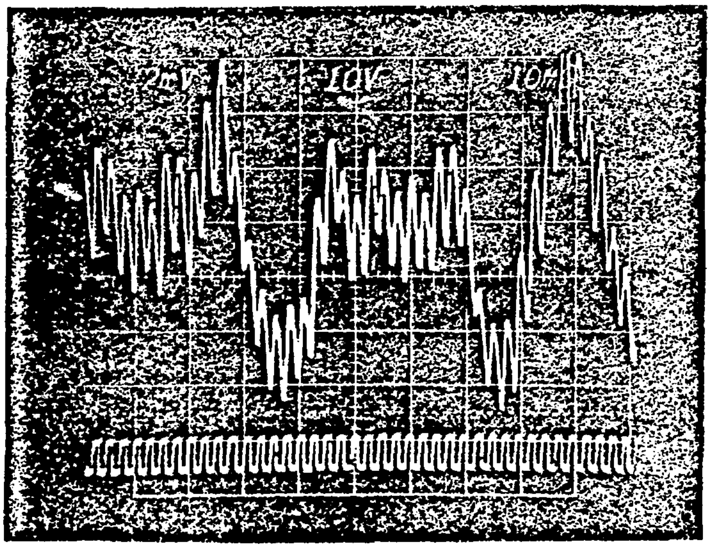

Figure 6. Oscilloscope Trace of Sensor output and Signal Conditioner Output at High Flow (Vortex Shedding Rate = 396 Hz)

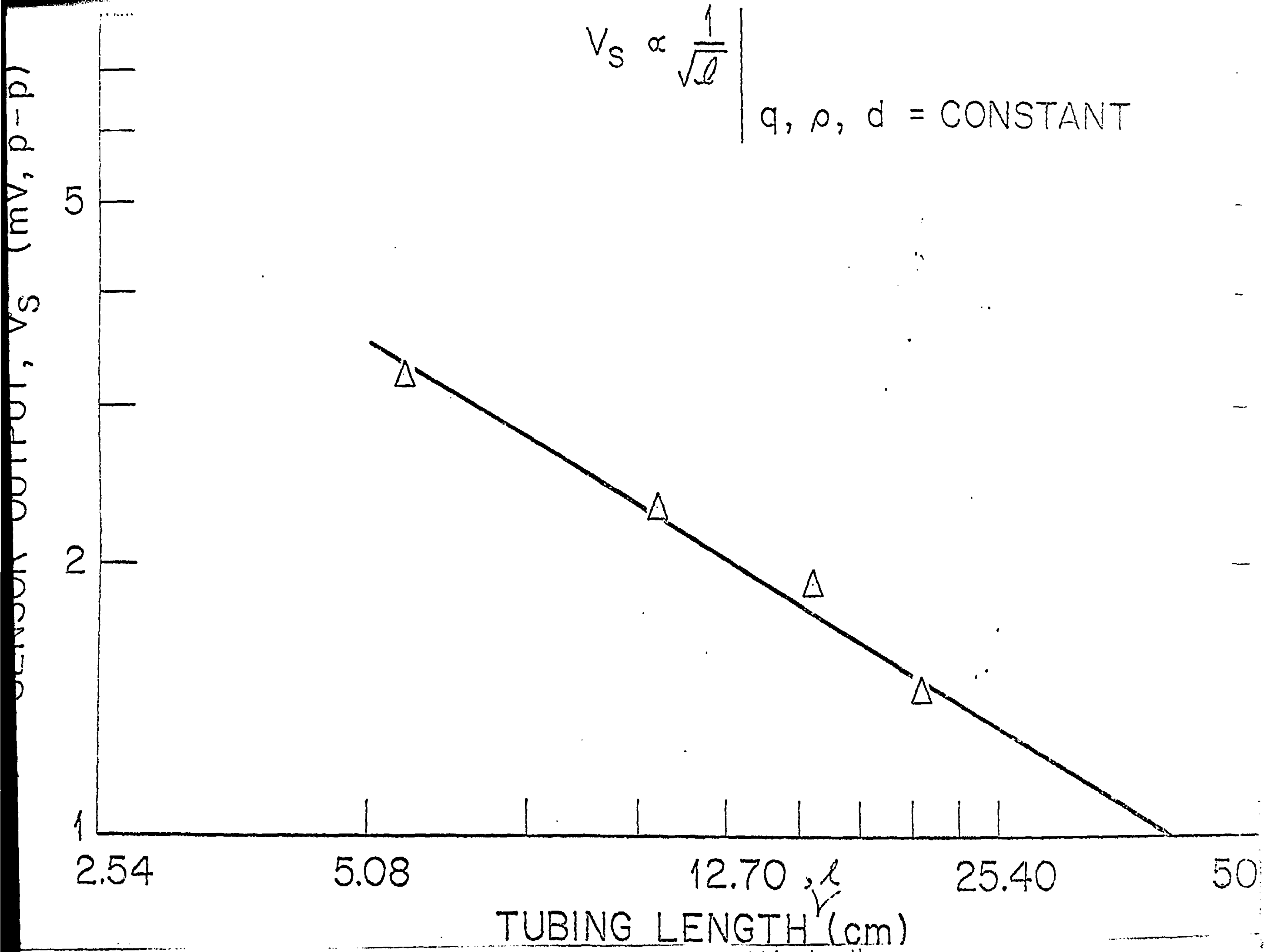

Figure 7. Relationship of V_s with Remoting Tubing Length

block prevented the use of tubing lengths less than 5 cm. It was observed that sensor signal/noise ratio decreased with increasing tubing length. This is another limiting factor determining the maximum tubing length.

Similarly, for constant tubing length, the variation of V_s with tubing diameter was determined. The results of these measurements are presented in Figure 8. V_s varies directly as the diameter, d. The diameter was varied from 0.16 to 0.64 cm.

Measurements were made in an attempt to determine the relationship between V_s and ρ, q. Such a relationship would permit the extrapolation of V_s over the entire range of flowing conditions in this application.

The variation of V_s with air flow at two densities is shown in Figure 9. The shape of these curves is typical of all the data. At all flows, as density increases, V_s increases. However, no well-defined relationship could be established for V_s as a function of density. Evidently, the three factors which determine sensitivity, the amplitude of vortex-generated pressure pulses, sensor thermal response, and remoting geometry attenuation interact in a complicated manner as density is varied.

Since signal performance could not be extrapolated from the air flow tests to the low density helium flowing conditions in this application, it was necessary to determine signal performance in actual helium tests. A sensor remoting geometry based upon Figure 7 and 8 was used for these tests.

The variation of V_s with helium flow at 0.1 MPa and 0.4 MPa and 10°C flowing conditions is shown in Figure 10. At this flowing temperature, the density at 0.1 MPa is equivalent to the density at 0.2 MPa and 350°C, the low density condition in the application. At the 0.4 MPa condition, V_s remained above threshold down to R_e = 6,000, and at the 0.1 MPa condition down to R_e = 9,000. Based upon these performance results, a final iteration of the sensor remoting geometry was incorporated in the VSFMs prior to calibration at the Colorado Engineering Experiment Station.

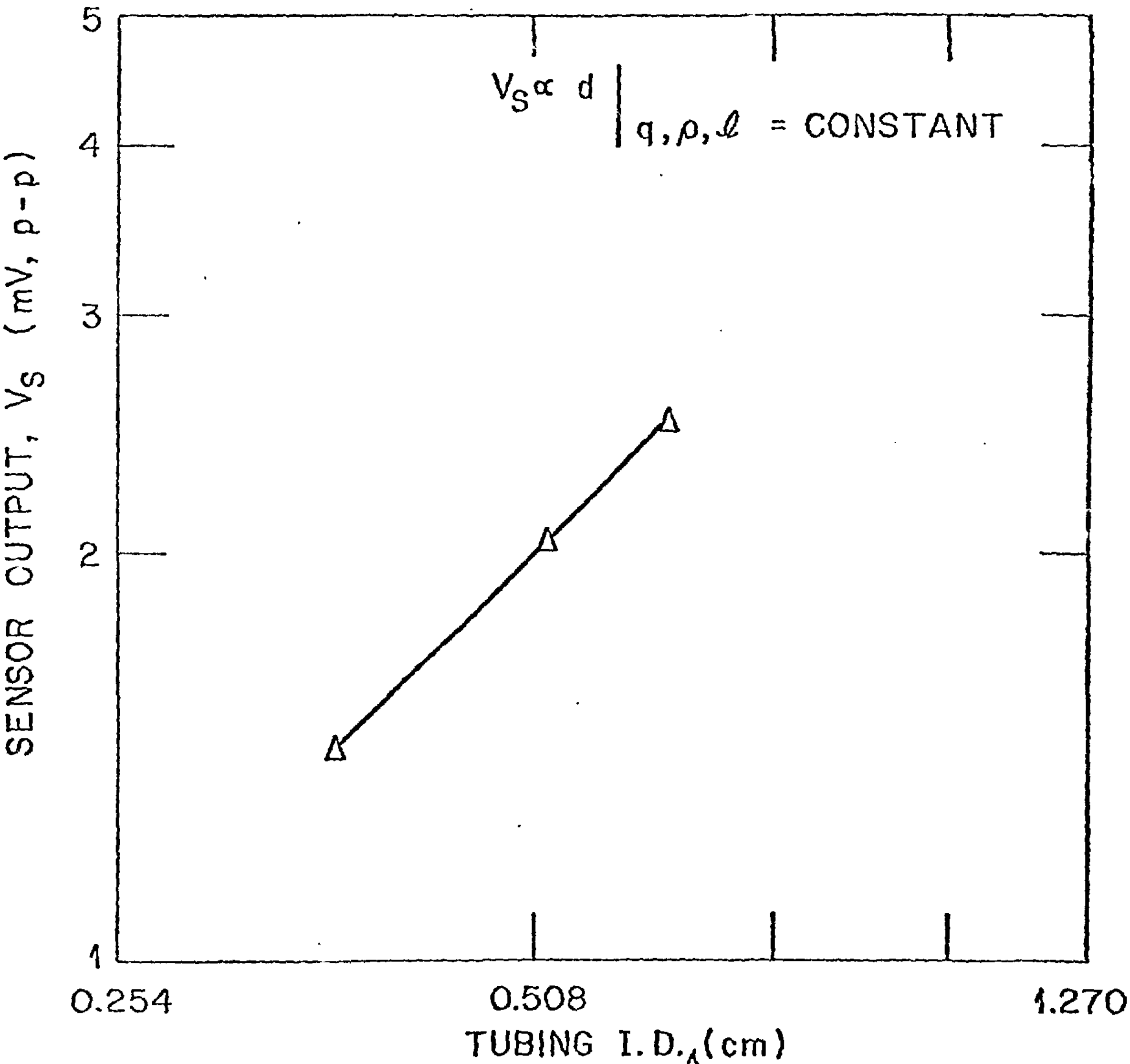

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Figure 8. Relationship of V_S with Remoting Tubing Diameter

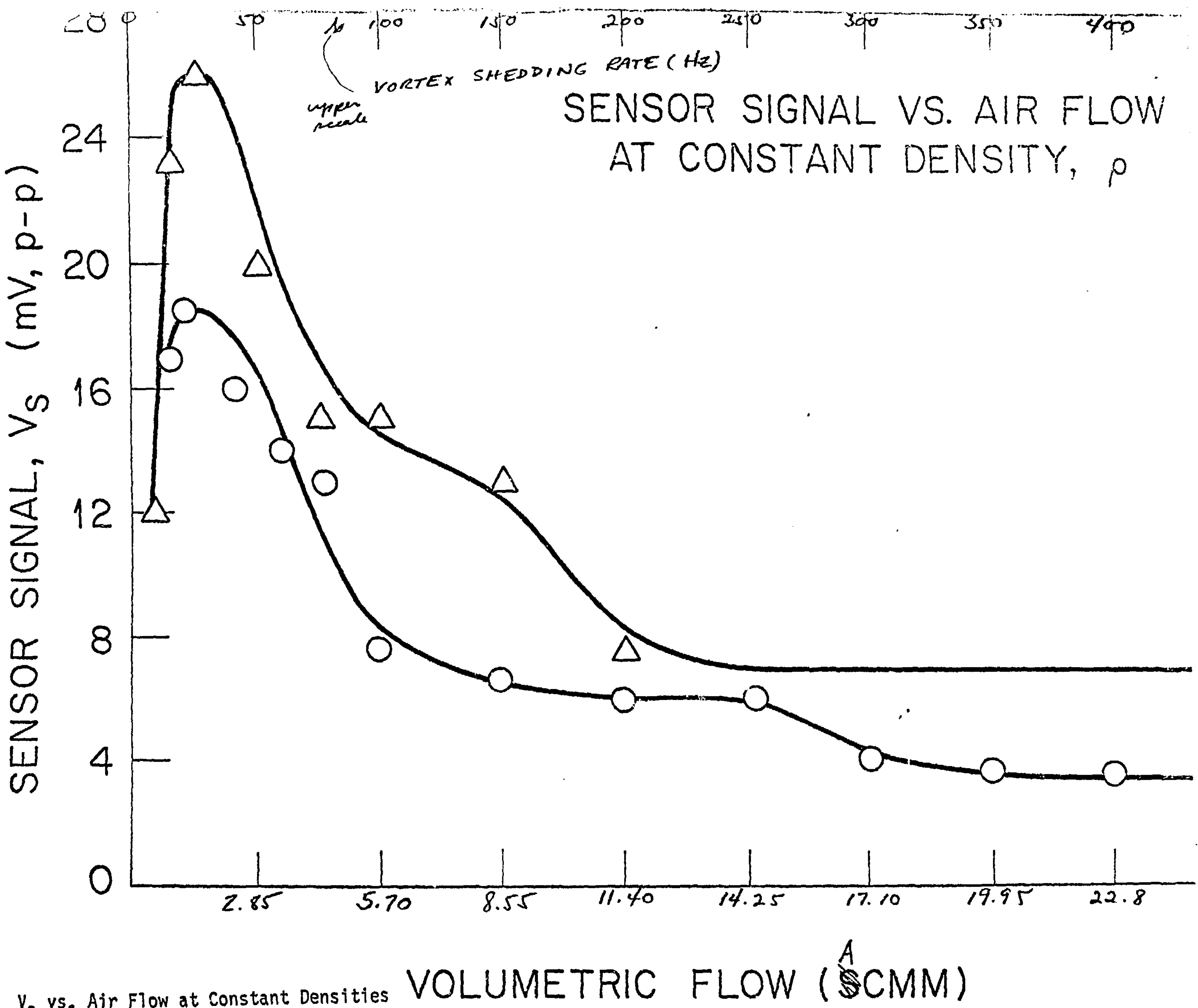

Figure 9. V_s vs. Air Flow at Constant Densities

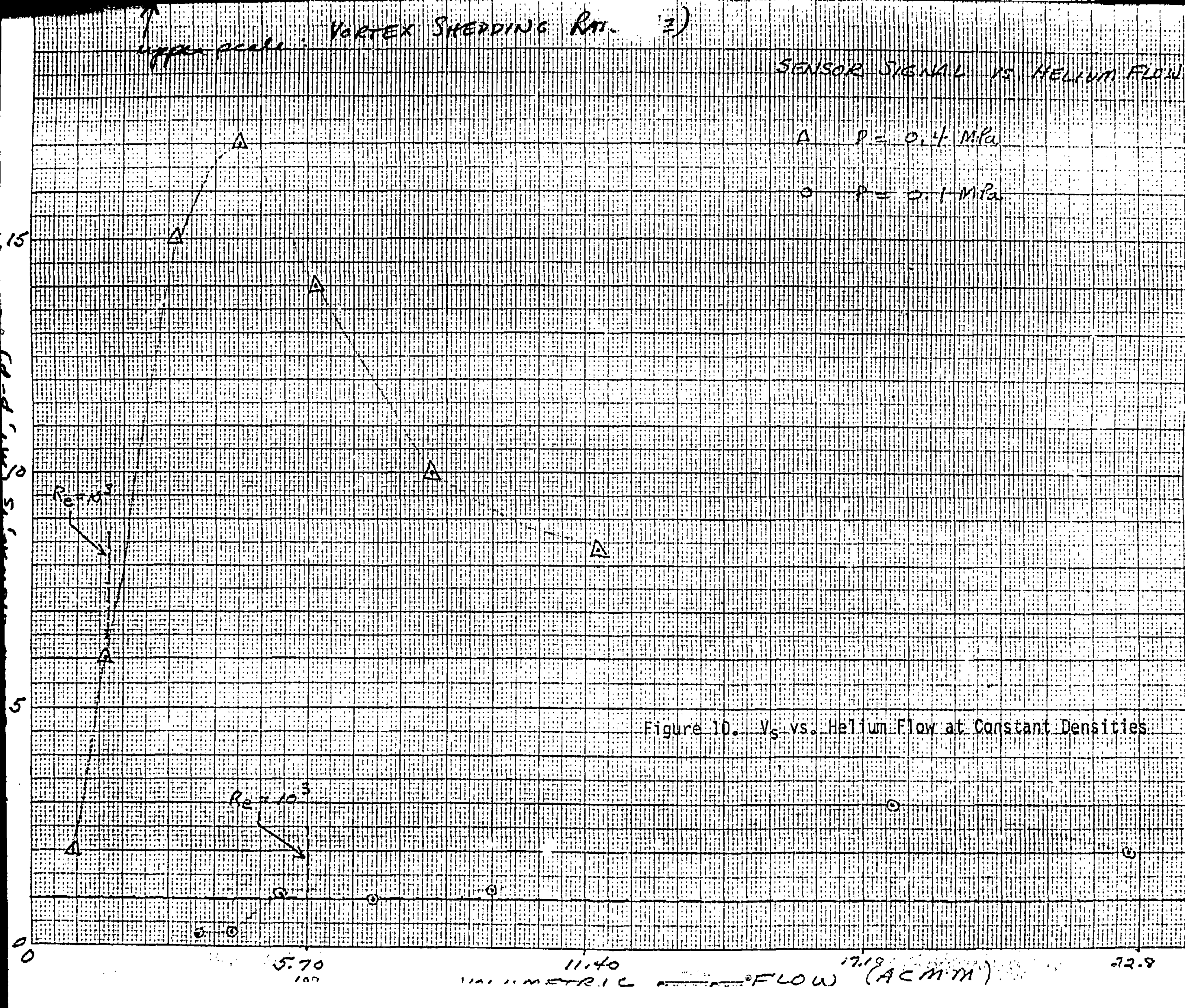

Figure 10. V_s vs. Helium Flow at Constant Densities

(Figure to be Supplied Upon Completion
of Tests in August 1980)

Figure 11. System Used for Measurement of Modified VSFM Accuracy

(Figure to be Supplied Upon Completion
of Tests in August 1980)

Figure 12. Modified VSFM Meter Factor vs. Flow at 0.2, 3.0, 9.0 MPa

During both the air and helium flow tests, the flowing temperature was elevated to as high as 290°C. A thermocouple mounted in the sensor block was used to measure the block temperature. An equilibrium temperature rise of only 9°C occurred at the highest flowing temperature.

FLOW MEASUREMENT ACCURACY

(NOTE TO REVIEWERS: Measurement of the volumetric flow accuracy of the modified VSFM is scheduled to be carried out in August 1980 at the Colorado Engineering Experiment Station. At that time the meter factor will be measured on both air and helium gas flow at 0.2, 3, and 9 MPa densities using an NBS traceable volumetric flow $\pm$ 0.25% standard. The flow range in these measurements will be 6 x 10^3 to 1 x 10^6 Reynolds Numbers. Subsequent to these tests, the results will be incorporated into this paper under the above heading. At that time, the abstract and conclusions will also be updated accordingly. Two figures will be presented in this section: a schematic diagram of the calibration system; and a set of curves that present the calibration data.)

PERFORMANCE EFFECTS NOT EVALUATED

Two performance effects were not evaluated that may have to be considered in other applications, namely:

- Erroneous volumetric flow rate indication due to double pulsing at very high flowing pressures
- Sensitivity degradation at extremely low and high ambient temperatures at the remoted sensor location

The former performance effect is inherrent in the single-ported sensor design (See Figure 13.) In the single-ported sensor design, a shed vortex is only sensed in the forward pressure pulse path. In the double-ported design, shed vortices are sensed in both forward and reverse paths. For a given volumetric flow, the single-ported sensor only detects half the actual number of vortices shed per unit time. Therefore, this design provides a better frequency response than the double-ported design. The difference between the two sensor designs is taken into account in the meter factor.

The small (0.5 mm diameter) weep hole in the single-ported design provides a bleed path for dissipation of the forward pressure pulse. At the

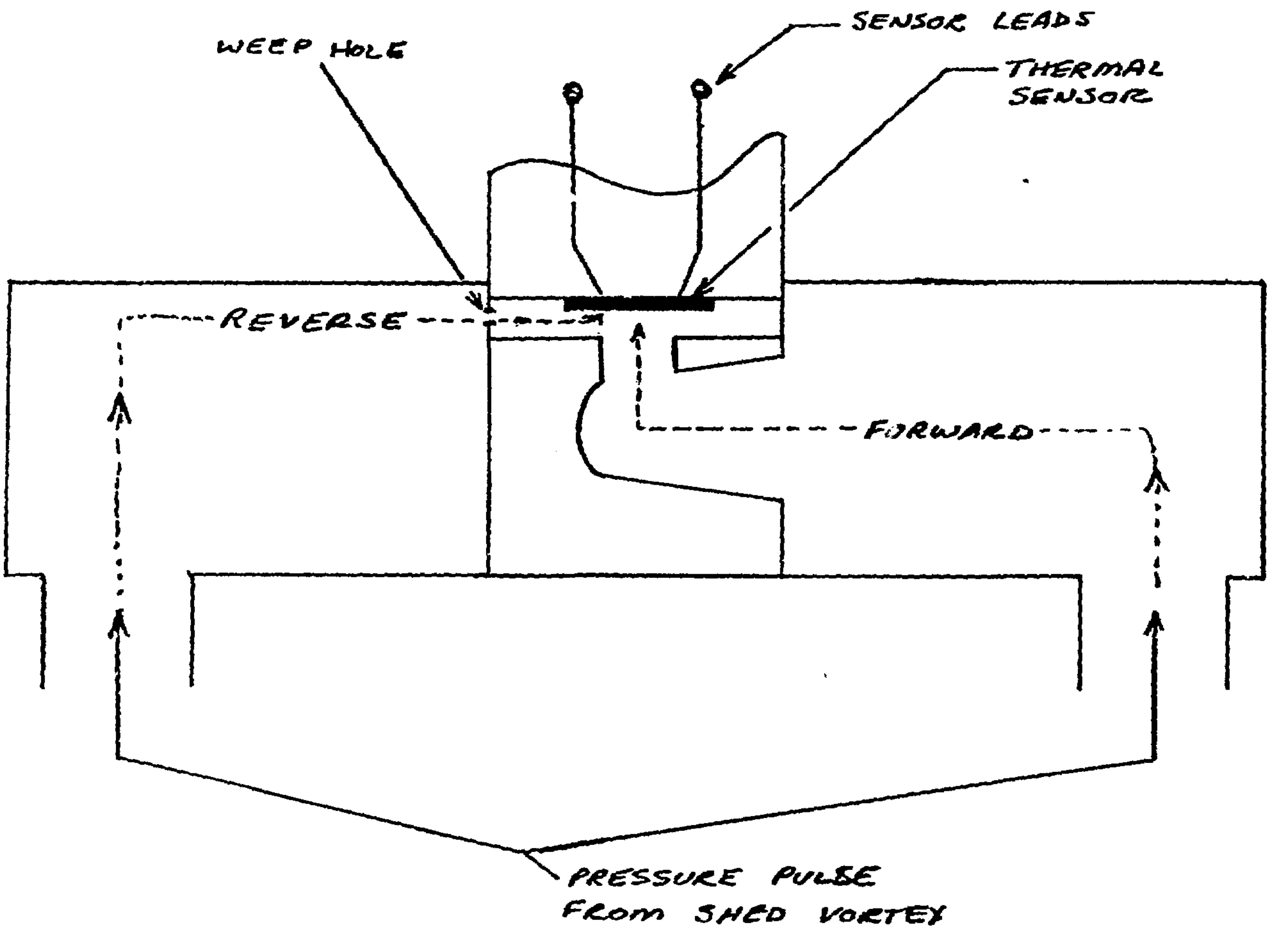

Figure 13. Schematic Diagram of Single-ported Sensor

same time, up to very high pressures (>20 MPa), the conductance from the reverse path is low enough to prevent detection from that direction. At very high pressures, this double pulsing phenomena will give an erroneous indication of twice the actual volumetric flow. The modified VSFM design employs shut off valves in the sensor block which could be used to circumvent this problem by providing an additional restriction in the reverse path. For a particular high pressure application, the threshold pressure for this effect should be empirically determined.

The latter performance effect not evaluated can limit the sensitivity of the remoted sensor in applications where the ambient temperature at the remoted sensor location exceeds certain limits. At very low ambient temperatures, heat transfer from the sensor to the ambient environment dominates over pressure pulse-induced heat transfer. At very high ambient temperatures, pressure-pulse-induced heat transfer becomes insufficient to produce an adequate signal. In applications where extreme ambient temperatures (below 0°C and above 100°C) occur, special attention should be given to this performance effect to avoid degradation of sensitivity.

CONCLUSIONS

A wide rangeability in high temperature gas flow measurement can be achieved using a VSFM with a remoted thermal sensor. A volumetric flow rangeability of 155:1 was demonstrated in this work.

Meter sensitivity was found to be a function of sensor remoting geometry. The minimum sensor signal for reliable operation was found to vary as $d/\sqrt{\ell}$ at constant flowing conditions. Practical minimum and maximum remoting lengths were established. The maximum remoting length was found to be about 40 cm.

The sensitivity was also found to be a complex function of the flowing parameters, density and volumetric flow. Generally sensitivity is an increasing function of density. The general shape of the minimum sensor signal versus volumetric flow curve is the same for all densities, except for extremely low densities.

Two performance effects, double-pulsing and sensitivity degradation due to extremely low or high ambient temperatures at the remoted sensor location, were not evaluated. These effects should be investigated in applications where they are likely to be encountered.

REFERENCES

1. S. P. Baker, Evaluation of Potential Helium Flowmeters for CFTL, Oak Ridge National Laboratory, Intra-Laboratory Correspondence, CFTL 78-99, 1978.

2. D. F. White, et al, The Vortex Shedding Flowmeter, Flow: Its Measurement and Control in Science and Industry, V.I, ed. R. B. Dowdell, Instrument Society of America, Pittsburgh, 1974, pp. 967-974.

3. R. D. Blevins, Flow-Induced Vibration, New York: Van Nostrand Reinhold Co., 1977, p. 259.

4. R. P. Benedict, Fundamentals of Temperature, Pressure, and Flow Measurements, 2nd ed. New York: Wiley, pp. 265-280, 1972.