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EVALUATION OF A CORIOLIS MASS FLOW METER FOR PULVERIZED COAL FLOWS

Topical Report

By
W. E. Baucum

December 1979
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The Energy Conversion Division
The University of Tennessee Space Institute
Tullahoma, Tennessee

U. S. DEPARTMENT OF ENERGY

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Principal Investigator

W. E. Baucum

Prepared by:

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ABSTRACT

An investigation of a new Coriolis mass flow meter was carried out to determine the feasibility of using it to meter the multi-phase flow of pulverized coal-transport gas mixtures. The Coriolis meter accurately measured dense phase coal flows on a continuous basis, producing an output which was a linear function of the coal flow. In less dense flows the meter monitored flow fluctuations and slugging, but when slugging became substantial the meter behaved erratically. Because the meter indicates flow fluctuation and slugging it promises to be a valuable instrument for evaluating new coal delivery systems as well as for monitoring and adjusting flow in established systems.

1. INTRODUCTION

In large scale coal conversion and combustion systems, process control requires a continuous high frequency monitoring of the mass flow of pulverized coal in its gas or liquid carrier. This multi-phase mass flow measurement represents a key parameter of coal systems, particularly for research systems like coal-fired Magnetohydrodynamic (MHD) energy conversion. A number of techniques have been considered for implementing the measurement of multi-phase flows. For coal, a timed measurement of the change in either the supply hopper weight or the volume of the supply has been used to measure the average mass flow in situations where high frequency fluctuations in flow are not critical. Other techniques rely on measuring ultrasonic Doppler shift, optical density, gamma-ray absorption, flow density, flow capacitance, and correlation techniques.[1] However, none of these techniques have been demonstrated to be applicable to the high frequency measurement of coal flow on a continuous basis.

Recently a new type of mass flow meter showed promise for applicability to coal flow measurements by successfully measuring the high frequency flow of high viscosity fluids in solid-liquid mixtures. This mass flow meter monitors the Coriolis force generated by the mass flux of any substance in a vibrating U-shaped tube.[2,3] This measurement is linearly proportional to mass flow rate and is independent of pressure, velocity, temperature, viscosity or density of the flowing medium. Thus, this mass flow meter appears well suited for applications where many parameters characterizing the coal flow are unknown. In addition this meter measures the approximate density of the flowing medium while measuring its mass flow.

The purpose of this investigation was to evaluate the Coriolis flow meter for high frequency, continuous metering of the mass flow of coal and N_2 carrier gas mixtures in coal-fired MHD supply systems. To identify and correct operational problems, the Coriolis meter was installed in the coal feed system of the University of Tennessee Space Institute (UTSI) MHD Research Facility and compared, under MHD power generation conditions, to load cell measurement of changes in the coal hopper weight. Next, a series of calibration experiments was performed over a range of flow rates and for several coal-to-transport gas ratios, R. Since then the calibrated meter has been used to establish, steady, and monitor fuel flow in the UTSI MHD Research Facility experiments.

2. FACILITY DESCRIPTION

2.1 Coriolis Meter

Figure 1 shows the Coriolis mass flow meter purchased from Micro Motion Inc. of Boulder, Colorado. The meter essentially consists of a U-shaped tube clamped at its top and vibrated at a constant frequency by a magnetic oscillator. Mass, M, flows in the tube with both an oscillating angular velocity, ω, and a bulk flow velocity, $\mathbf{v}$, along radii of the arc described by the oscillating tube, thus generating oscillating, oppositely directed Coriolis forces on the tube legs. The Coriolis forces twist the tube about its axis of symmetry by an amount which is linearly proportional to the forces, and thus to the mass flow rate. The mass flow rate is measured by measuring the twist of the U-tube.[1,2] For increased sensitivity, the Micro-Motion Inc. meter optically measures the tube twist at the center of the oscillation arc where the angular velocity, Coriolis forces, and tube twist are maximized.

The density of the flowing medium can also be determined by measuring the vibration frequency of the U-shaped tube through its relationship to the elastic constants of the tube and the density of the flowing medium.[1,2] This measurement may be somewhat approximate, however, because the elastic constants of the tube, which depend on the temperature of the tube and its contents, can only be approximated when spatial and temporal temperature variations occur.

The U-tube is sized for a particular flow range to obtain a dense flowing medium while minimizing tube pressure drop. The tube size in the tested units is 1/2" I. D. for a flow range of 0 to 1.5 lb/sec. Furthermore, based on the Nyquist criteria, the flow rate can theoretically be measured up to a frequency which is half the U-tube vibrator frequency, allowing a typical response range of 0 to 24 Hz.

2.2 Coal Flow System

The coal flow system is shown in Figures 2 and 3. The system was designed to deliver pulverized coal to the UTSI MHD Research Facility combustor at adjustable rates between 0.3 and 1.1 lb/sec. The system has two coal hoppers, each with 2000 lb capacity. By pressurizing the hopper with nitrogen, coal is forced through 3/4" diameter (0.652" I. D.) stainless steel tubing. Near the base of the coal hoppers, transport nitrogen can be injected into the tubing to help transport the pulverized coal through the supply tubing. The coal flow rate is controlled by adjusting the hopper pressure (up to 100 psig) and the transport gas pressure (up to 115 psig). For most of the tests the Coriolis flow meter was installed in the supply tubing just downstream of the transport gas injection. For several tests, however, the Coriolis meter was installed upstream of the transport gas injection.

To calibrate the Coriolis meter for coal-transport gas flows the coal flow system was used to deliver pulverized coal to the calibrator shown in Figure 4. Coal flowed from the coal line through a variable ball valve which was used in conjunction with the coal hopper pressure to control the flow rate. Two other ball valves directed the coal flow into either the drum storage or the weighing barrel, which sat on a scale used to measure the gain in barrel weight. During calibration the coal flow initially was sent to the drum storage. When the Coriolis meter indicated coal flow at a preselected flow rate, the coal was diverted to the weighing barrel for two minutes. The average coal flow was calculated from the weight change of the barrel, and compared to the Coriolis meter output, to calibrate the meter.

2.3 Data Acquisition

Both of the Coriolis meter analog output voltages, indicating mass flow rate and fluid density, were recorded. In addition analog signals were recorded to monitor coal hopper pressure and weight; coal line pressures; transport gas total pressure, temperature, and orifice pressure differential; as well as valve positions in the coal delivery system. All data were recorded by digitizing the analog signals at scan rates of either 1 Hz or 10 Hz. The digital data acquisition system consisted of signal conditioning amplifiers, a signal multiplexer, an analog to digital converter, and a Data General Eclipse S/239 computer. The computer stored the data on magnetic tape during acquisition for later analysis.

The coal line pressures and transport gas data were also recorded on magnetic tape using a Honeywell Model 5600C tape recorder with a frequency response of 5 KHz.

3. RESULTS

Before attempting to measure coal flow rates, the Coriolis mass flow meter was adjusted and calibrated using water as the flowing medium. The meter output voltage was adjusted to 0 while trying to maintain 0 flow in the vibrating tube. Then the output was recorded for flow rates ranging from 0.17 to 1.25 lb/sec and a least-squares curve fit resulted in the calibration equation:

$$M = 0.01 + 0.30V \qquad (1)$$

where M is the water mass flow rate in lb/sec and V is the flow meter output in volts. Equation (1) confirmed the predicted linearity of the meter response.

To identify and attempt to correct problems in Coriolis meter behavior under MHD test conditions the meter was installed in the UTSI MHD research facility coal supply system. The supply system was operated at conditions which were selected to simulate MHD power generation coal flows. However, flow was not supplied to a pressurized combustor, but was delivered to an open barrel. Therefore, normal research facility operating parameters could not be used and considerable experimentation with operating parameters was required.

For the problem identification tests the Coriolis meter was calibrated by comparing the meter output with load cell measurements of coal hopper weight loss. Because the coal line and hoppers vibrate under MHD generation conditions the load cell measurements were averaged over 7 sec. intervals to eliminate vibration measurements from weight measurements. Since the weight change of the coal hopper in 7 sec. is only a small fraction of the total hopper weight this calibration is rather imprecise, but load cell calibration could still help to identify and correct problems which might be encountered when using the Coriolis meter as MHD power generation instrumentation. These problems might include erratic response, uncorrelated response to coal flow, or non-linear response.

In the initial phase of load cell calibration the Coriolis meter was installed beneath the coal hoppers just downstream of the transport gas injection. Tables I and II indicate the resulting erratic behavior of the meter. To determine if slugs of nitrogen and coal flow might be causing this behavior the flow meter was moved upstream of the transport nitrogen injection. The metered flow rates agreed well with the load cell measurements, indicating that "slugging" of the coal and transport gas was responsible for the erratic meter behavior. Similar erratic behavior had been observed for the Coriolis meter with fluid flows having a large bubble content. This was traced to a damping of the U-tube oscillations with extreme slugging flow.[4] Therefore, additional calibration of the meter mounted downstream of the transport gas injector was carried out while monitoring the U-tube oscillation. The oscillations proved to be damped when erratic meter behavior occurred, preventing the meter from properly responding to flows with extreme slugging. However, since slugging is not desired in combustor coal supply systems the meter should be a good instrument for evaluating such supply systems because it will indicate slugging of the flows up to the onset of extreme slugging. It should be noted that slugging has been observed in the Research facility coal flow system in the past. Flow system redesign, such as placing a line size change or other discontinuity in the coal line prior to the combustor injection has so far been successful in eliminating the slugging problem.

The Coriolis meter was subsequently installed upstream of the transport gas injector and observed in two actual MHD power generation experiments. Although the meter flow rates compared favorably to load cell measurements several additional operational problems were identified. First, a drift in the calibration zero was identified and traced to meter vibration sensitivity. This problem was corrected by rigidly mounting it to two large welded I-beams. Second, moisture collected inside the meter and corroded the circuit board. To correct this problem the meter was redesigned by the manufacturer, to better protect the electronics, and the meter was moved into the test area for weather protection. Although installation of the meter in the test area prevented metering coal flow upstream of the carrier gas injection, where the flow remains stable, the test area installation should allow the Coriolis meter to be used to adjust the flow to the desired coal rate while avoiding slugging and other flow oscillations.

To actually calibrate the redesigned Coriolis meter for coal flow the meter was operated with the coal flow calibrator at up to 1.34 lb/sec flow at several transport gas-to-coal ratios ranging from near 0 to 1/50 by weight. Because pulverized coal has some gaseous content it was not possible to precisely determine the gas content of the coal-gas flow, but it was assumed that essentially all the transport gas was introduced by the injection of nitrogen into the coal flow. Therefore, the flow of nitrogen to both the coal hoppers and the transport gas line was measured to define the transport gas content of the coal-gas flow.

With no transport gas injection the Coriolis meter was calibrated for coal mass flows of 1.34, 0.78 and 0.45 lb/sec. Figure 5 shows time plots of the Coriolis mass flow meter output for the three flow rates. Although some fluctuation in the output is apparent, the flow rate appears to be relatively constant. The density output of the Coriolis meter also indicated fairly constant density of the flowing medium. The average mass flows and average Coriolis meter voltages calculated for the calibration points are plotted in Figure 6. The calibration obtained is linear and a least-square curve fit gave the equation:

$$M = -0.1 + 0.346V \qquad (2)$$

where M is the mass flow rate in lb/sec and V is the average meter output in volts. The correlation factor of the curve fit was 0.99, and the expected variance of the meter was 0.135 volts^2.

The coal supply system data were also examined during calibration without transport gas injection. Figure 7 is a plot of the pressure differential between the coal hopper and the downstream coal line vs. average mass flow. The linear relationship exhibited suggests that, for no transportation gas injection, coal line pressure drop could be used to meter average mass flow rates. Measurements of the bulk flow of pressurizing nitrogen into the coal hopper were also compared to bulk coal flow. These flows were essentially equal, indicating that the nitrogen used to pressurize the coal hoppers did not mix with the pulverized coal and the density of the pulverized coal was not decreased when transport gas was not injected into the coal line.

By varying the transport gas injection, the Coriolis meter response was examined for different coal to injected transport gas ratios, R. Figures 8 and 9 show time plots of the Coriolis meter output for four coal-to-gas ratios. A comparison with Figure 5 shows that the metered flow fluctuations greatly increase with increases in the amount of transport gas injected (i.e. as R decreased). In fact the Coriolis meter output exceeds its limit at mixture ratios less than 128/1. For moderate mixture ratios the Coriolis meter indicated the existence of periods of fairly uniform frequency fluctuations in the flow. Figure 10 shows one of these periods compared to the measured coal line pressure and the Coriolis meter flow density signal. The observable correlation of flow rate, line pressure, and flow density in Figure 10 seems to indicate that slugs of transport gas and coal alternately flow in the coal line between the flow meter and the line pressure transducers. The observable correlations also indicate that the flow meter has a good frequency response to variations in mass flow for high to moderate mixture ratios, where flow slugging is not severe enough to cause erratic response.

Following identification of meter operating characteristics and calibration, procedures were established to use the meter to control the coal flow in UTSI MHD Research Facility experiments. Coal flow is initiated by starting transport nitrogen flow while pressurizing the coal hoppers. Once a continuing coal-gas flow is established the coal and nitrogen flows are adjusted so that the Coriolis meter indicates approximately the desired average coal flow rate. Then by observing the meter, the nitrogen flow is reduced until the flow becomes steady. Final flow rate adjustments are made by changing hopper pressure, and the Coriolis meter is used to monitor the flow steadiness. The Coriolis meter has been used in this manner in all recent Research Facility coal burning experiments, without problems.

The Coriolis meter was successfully used to evaluate the UTSI MHD Research Facility coal supply system and promises to be useful for evaluating new coal delivery systems. Such an evaluation is planned to map out the flow range and slugging limits of new coal systems for the Coal-Fired Flow Facility, a large MHD facility presently being completed at UTSI. During this evaluation the meter will be used for monitoring coal flows at coal to transport gas injection ratios ranging from dense phase to below 50:1. Coriolis meters will also be used for coal flow rate control and monitoring in the Coal-Fired Flow Facility, as is presently done in the Research Facility.

4. CONCLUSIONS

A Coriolis mass flow meter has demonstrated the capability of high frequency continuous metering of the mass flow of pulverized coal in a coal-fired MHD supply system. A linear calibration was obtained for the metering of dense phase coal flow (i.e. with no transport gas injection). The Coriolis meter followed the fluctuations of coal and transport gas flows for limited transport gas injection, but for low coal-to-gas ratios the meter behavior became erratic when slugging was sufficient to damp the meter U-tube oscillations. Since slugging is not desired in coal delivery systems the Coriolis meter shows promise for system evaluation by detecting slugging in these systems as well as by determining operational conditions when the coal and transport gas are well mixed. (It should be noted that slugging has been experienced in the past coal flow system and has been eliminated with redesign of the flow system.) The meter indiicated that excessive slugging could occur in the UTSI MHD Research Facility coal supply system and it has been used successfully for establishing the desired coal flow rates without slugging or other flow oscillations.

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TABLE I

Initial Load-Cell Calibration

Hopper Pressure (psig)	Hopper Value Setting (% Open)	Transport Gas Pressure (psig)	Behavior of Mass Flow Meter
110	50	125	Indicated flow beginning at 0.7 lb/sec and increasing to 3 lb/sec at flow termination
65	100	75	Random 0-1.5 lb/sec mass flows
30	28	40	Full Scale Reading

TABLE II

Summary of Experimental Results

Coal Mass Flow (lb/sec)	Nitrogen Mass Flow (lb/sec)	Ratio (Coal/N_2)	Hopper Pressure (psig)	Coal Line Pressure (psig)	Meter Response
0.45	0	-	60	36	very stable
0.78	0	-	80	46	very stable
1.34	0	-	80	37	very stable
1.2	0.0048	250/1	78	17	stable
0.94	0.0073	128/1	78	23	unstable
0.76	0.0087	87/1	78	25	erratic
0.6	0.01	60/1	78	25	erratic
0.6	0.012	49/1	78	54	erratic

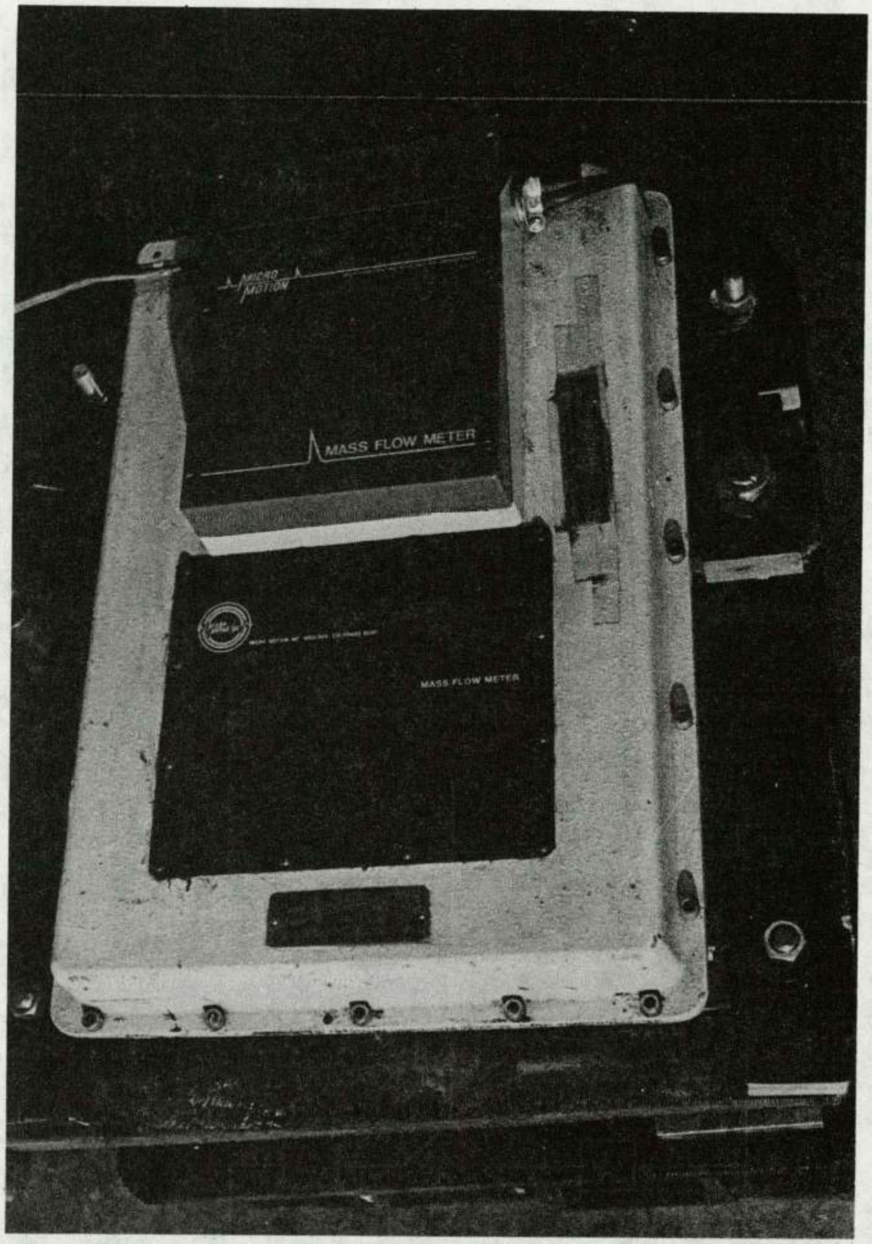

Figure 1. Coriolis Mass Flow Meter

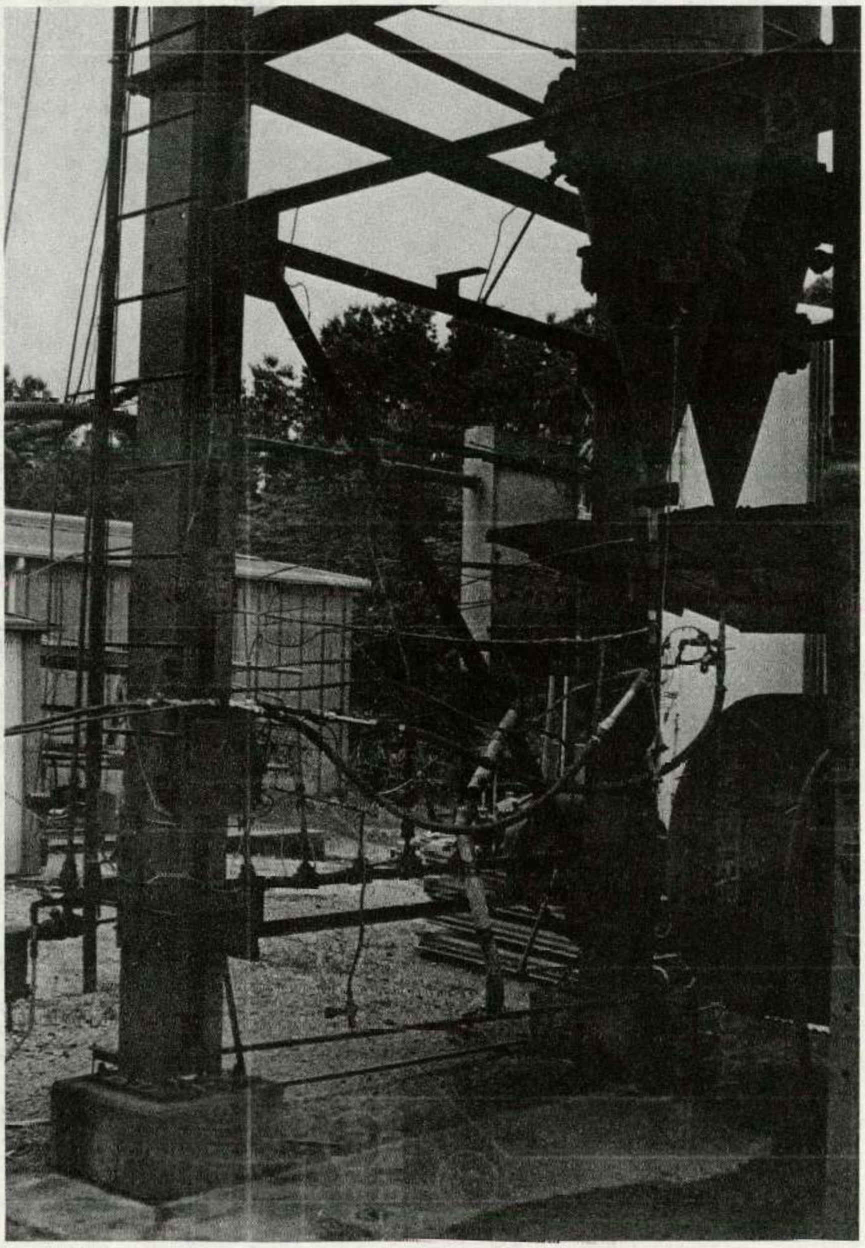

Figure 2. Coal Delivery System

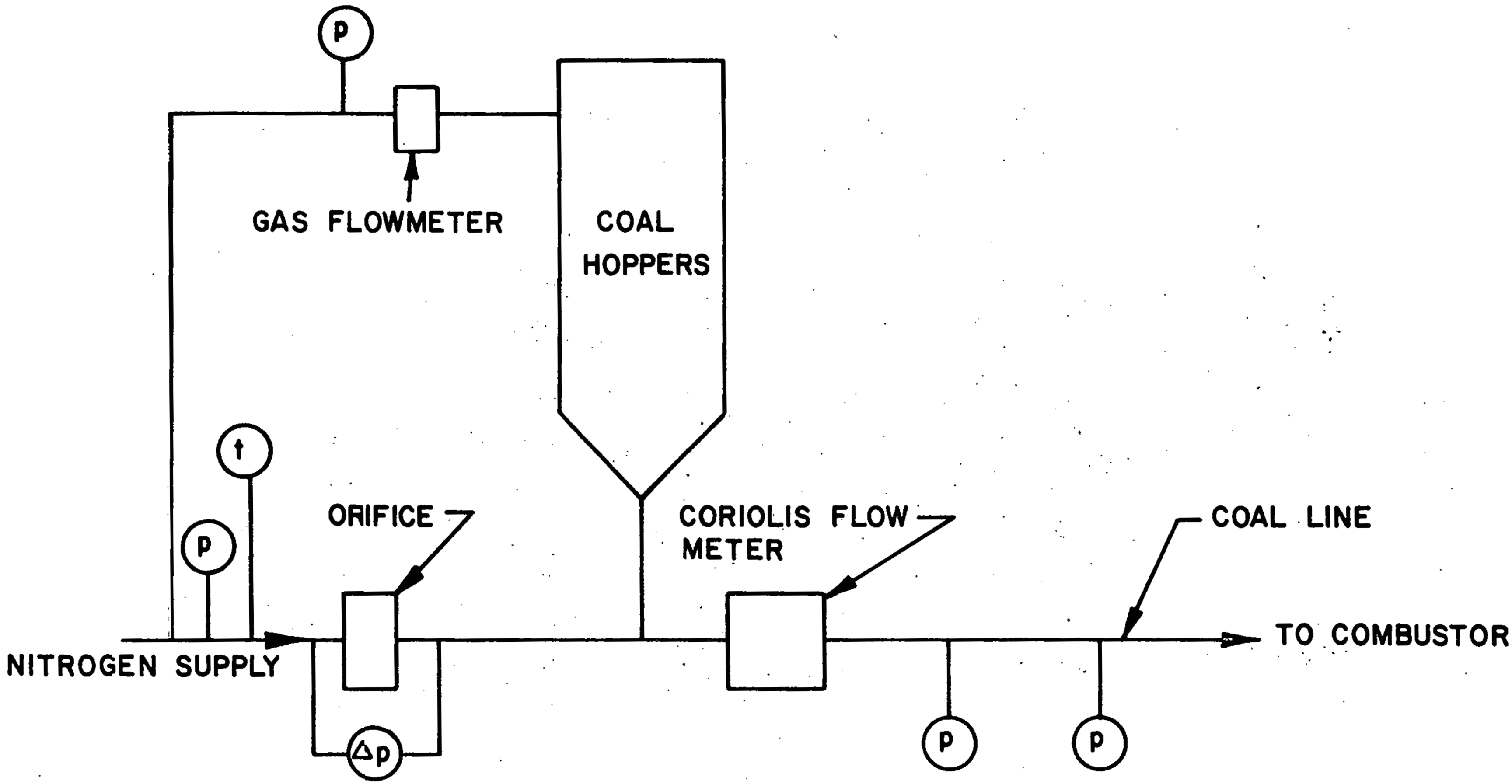

Figure 3. Coal System Schematic

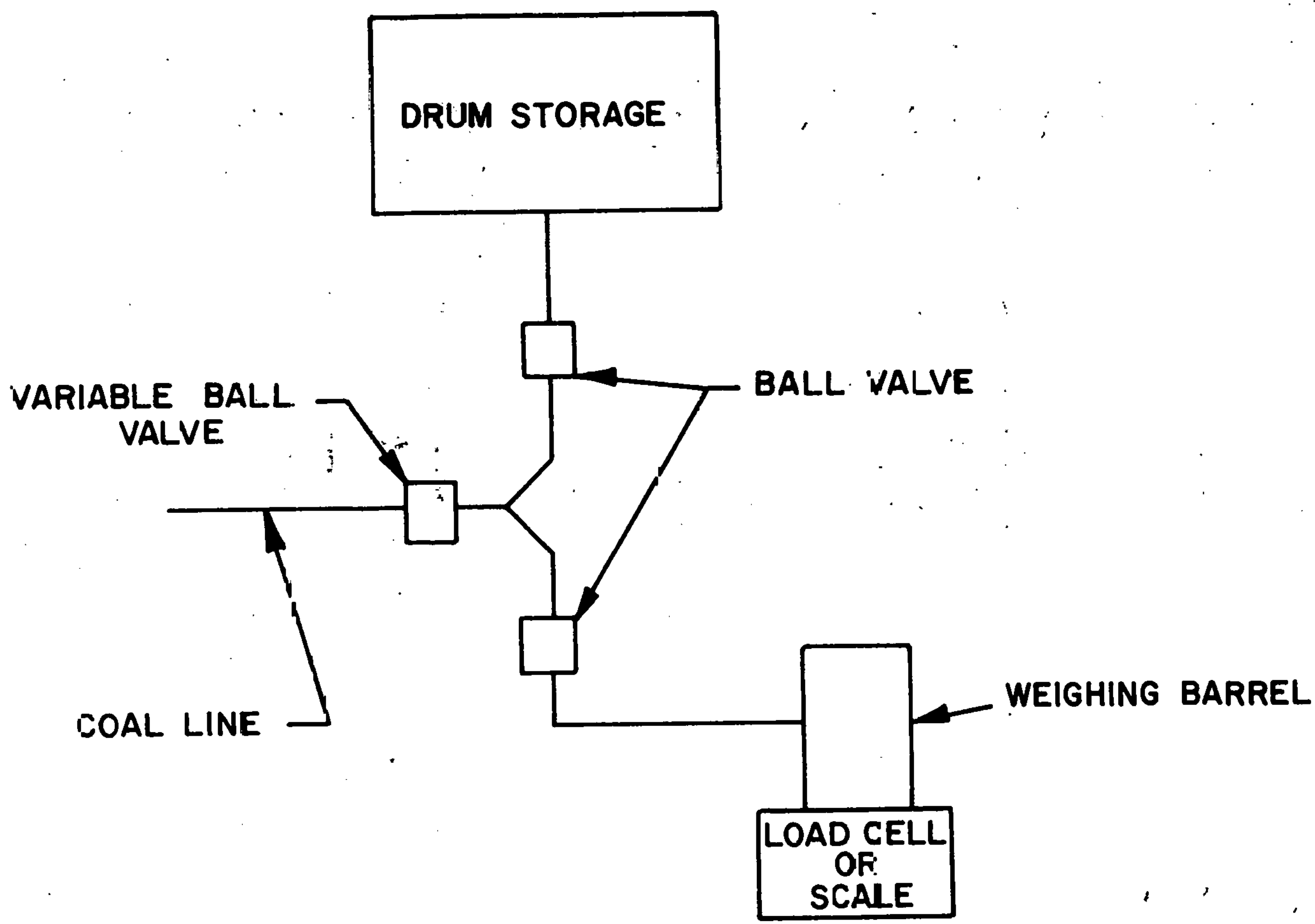

Figure 4. Mass Flow Meter Calibrator

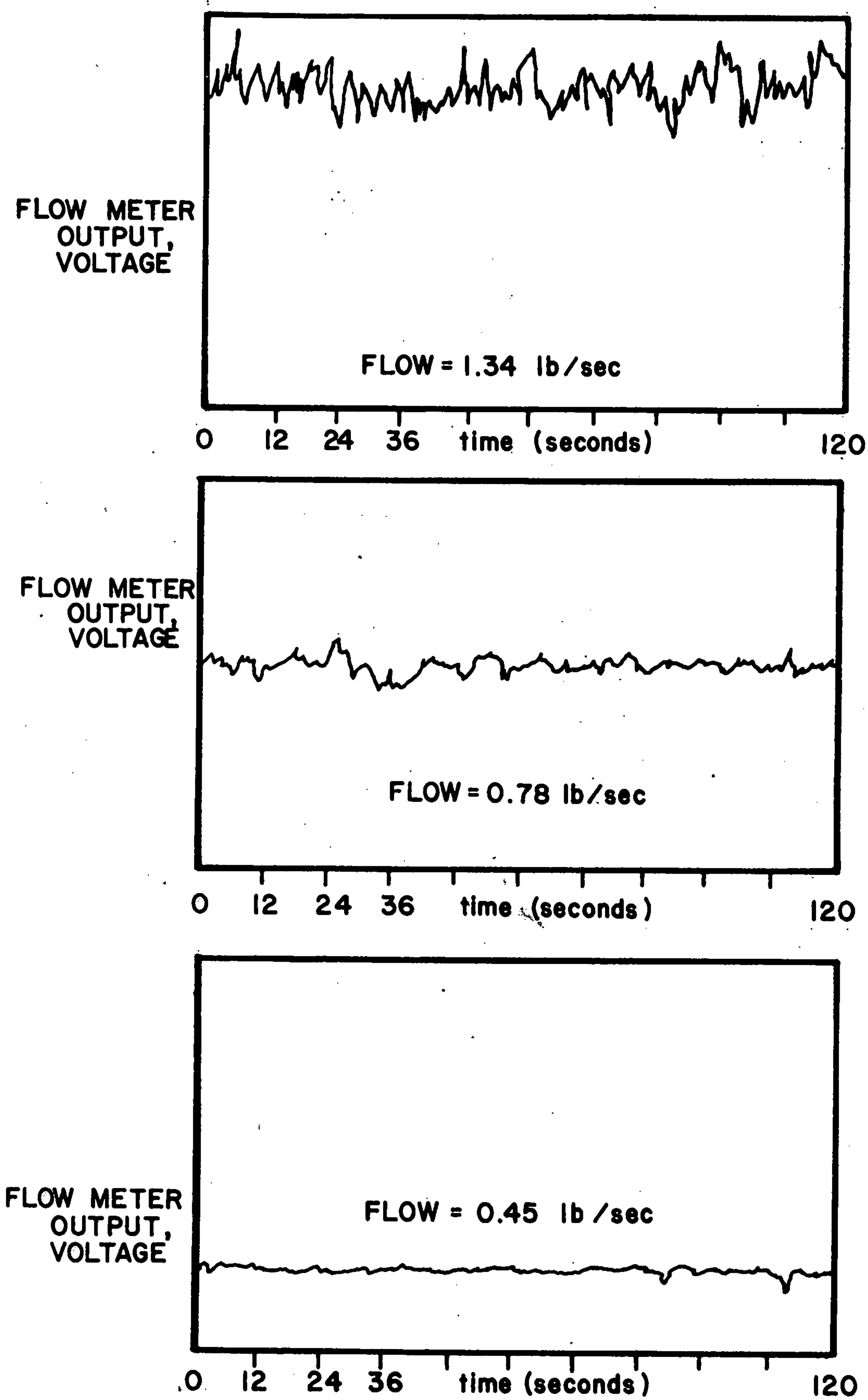

Figure 5. Coriolis Meter Fluctuations for Pulverized Coal Flow

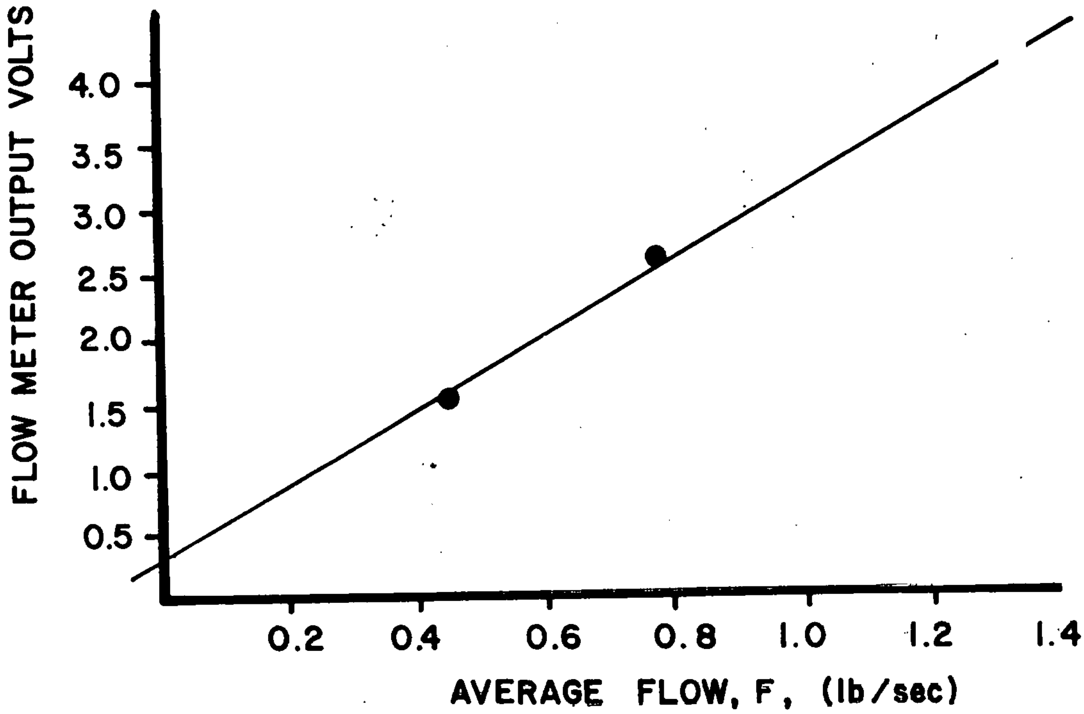

Figure 6. Mass Flow Meter Calibration

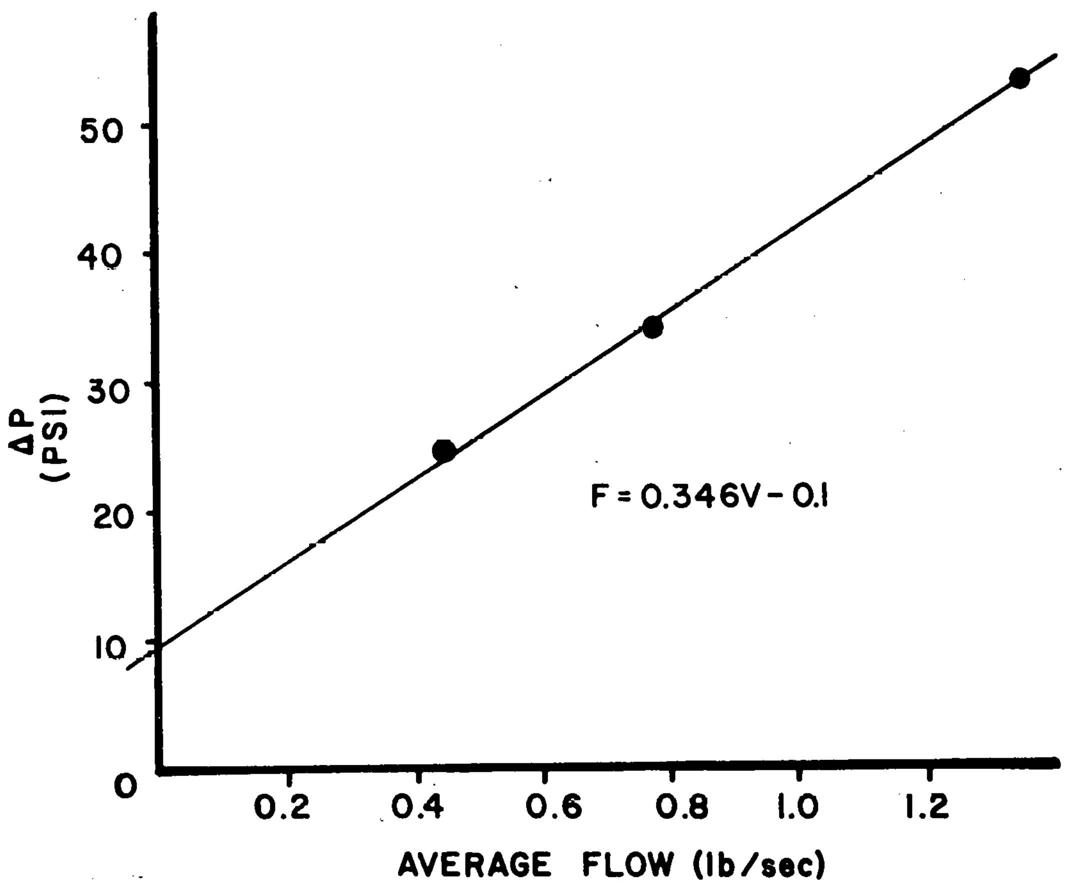

Figure 7. Pressure Differential Calibration

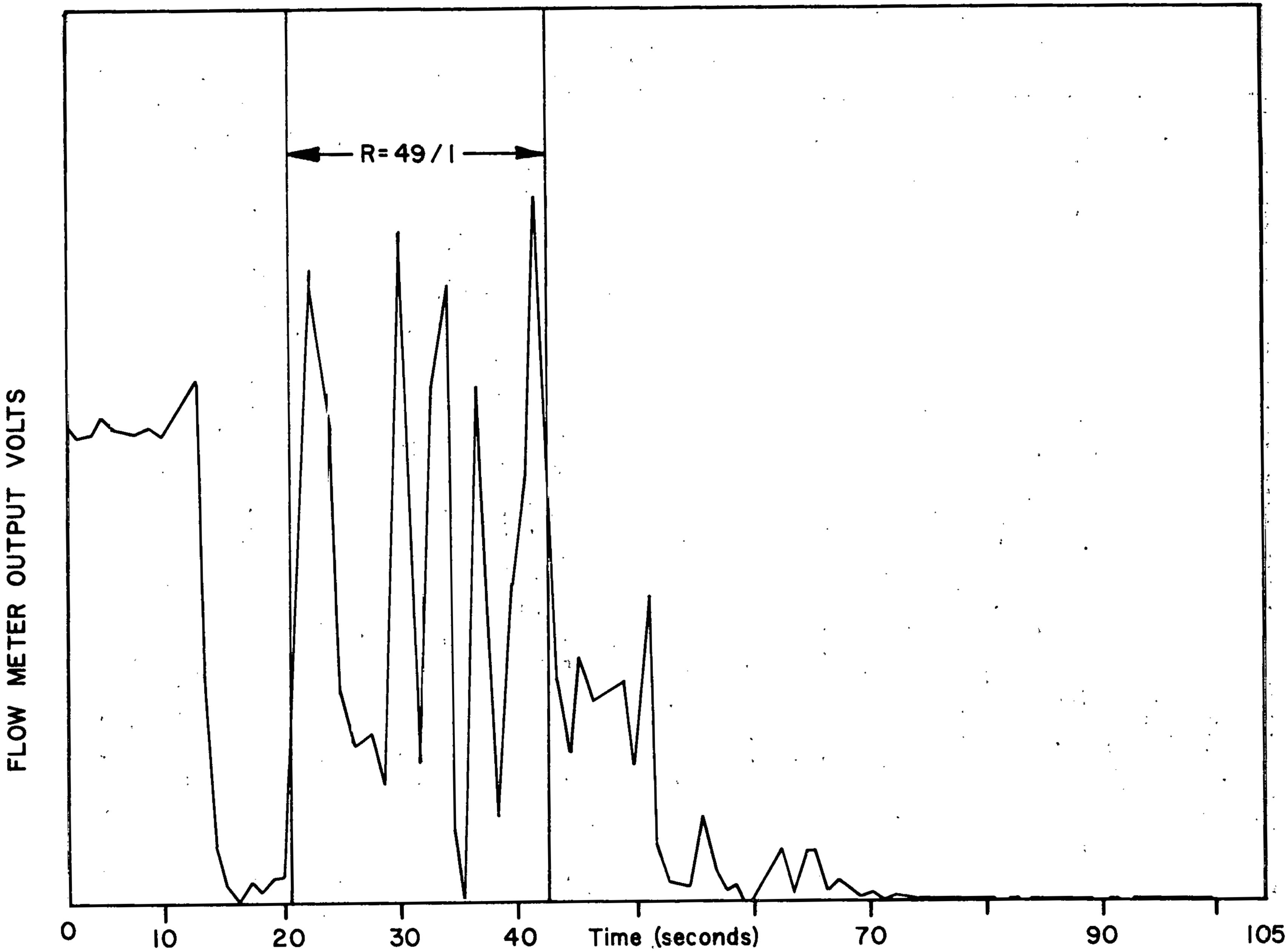

Figure 8. Flow Meter Output for 49/1 Mixture Ratio, R

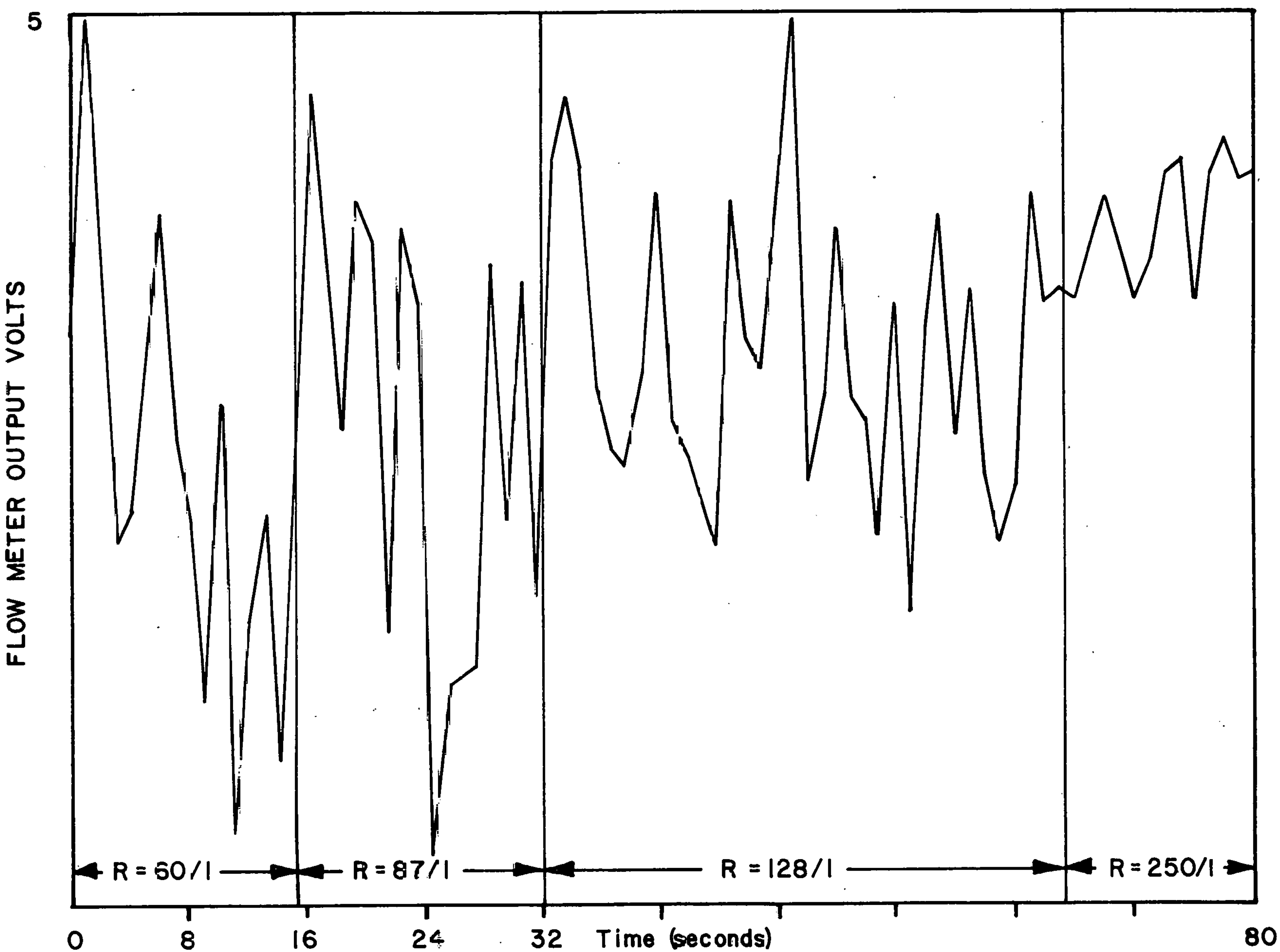

Figure 9. Flow Meter Output for Different Mixture Ratios, R

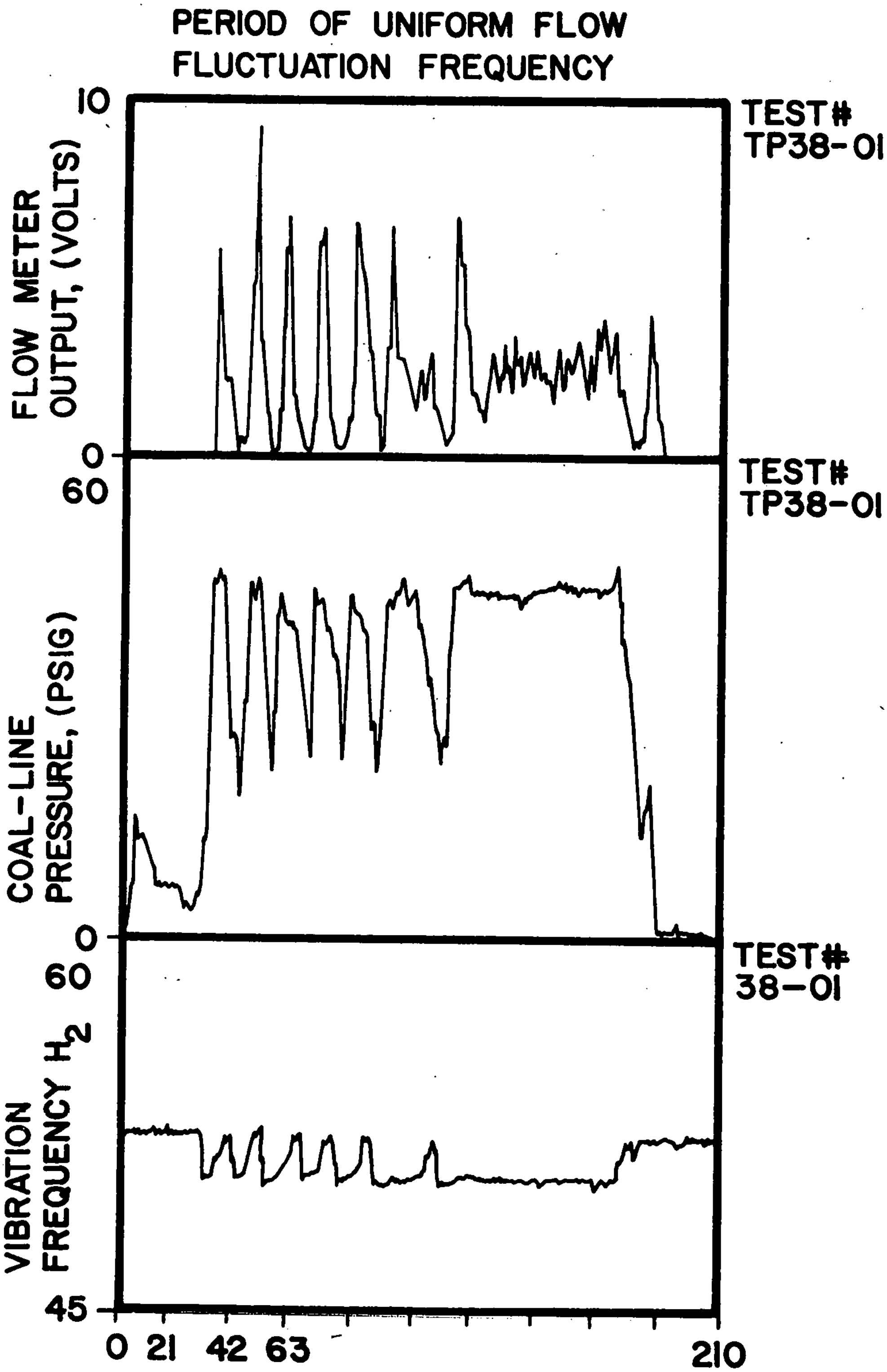

Figure 10. Comparison of Flowmeter Mass Flow, Coal Line Pressure and Flow Density Measurements

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