Georgia Institute of Technology
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# AE2610 Introduction to Experimental Methods in Aerospace

# COMBUSTION DYNAMICS IN A RIJKE TUBE

## Objectives

This laboratory introduces the measurement of periodic fluctuating properties and acoustic oscillations. In addition, this experiment involves measurements in a reacting flow produced in a Rijke tube, pulse combustor. Piezoelectric transducers are used to monitor the acoustic pressure fluctuations, while radiation emitted by the flame and detected with a photomultiplier tube provides a qualitative measure of the chemical reaction rate or heat (chemical energy) release rate. Furthermore, students will be exposed to the use of rotameters for fluid flowrate measurements.

> **NOTE: All experiments with combustion are potentially hazardous. Please follow all the precautions that need to be taken and which are outlined in the section on safety considerations.**

## Background

Pulse Combustors and Rijke Tube

In a pulse combustor, the combustion intensity and, therefore, the (chemical) heat release rate fluctuate periodically with time. The resulting pulsed heat release causes the pressure in the combustor to oscillate in time, i.e., like a sine wave. In addition, a fluctuating, acoustic velocity generated by the pulsations is superimposed upon any mean flow rate. These fluid mechanical oscillations, in turn, can reinforce the heat release fluctuations. These three effects, namely heat release, pressure and velocity oscillations are, thus, coupled and feed on one another. The strength of the oscillations thus grows until this "acoustic driving" is balanced by the acoustic losses in the combustor.

Such a combustor has many advantages. For example, the combustion intensity is increased because of the better mixing between fuel and air. In addition, heat transfer to the wall is increased since the oscillating acoustic velocity component strips away the otherwise insulating boundary layer. Finally, the pulsations tend to push the combustion products out of

the exhaust. In contrast, a steady combustor creates venting by convection of the hot exhaust through a chimney, which means that a significant part of the heat (up to 30%) must remain in the exhaust and is, therefore, lost.

The pulse combustor used in this experiment is a Rijke tube, named after its Dutch inventor. It consists basically of a long, vertical tube open at both ends with a source of heat release, e.g., a burner or a heating wire, *placed at roughly one quarter of its length from the lower end*. If a tube with two open ends is acoustically excited, it acts like an organ pipe. Thus the pressure in the pipe will vary with time.

In general, we can take the pressure at any point and decompose into a time-averaged component ( $\bar{p}$ ) and a time-dependent component ($p'$),

$$p(t) = \bar{p} + p'(t). \tag{1}$$

For our case, where the pipe is resonating, we get a standing acoustic wave inside the pipe. The wavelength $\lambda$ of the acoustic wave is twice the pipe length* (see Figure 1). The frequency $f$ of the wave is related to the wavelength by the relation

$$f = a/\lambda = a/2L. \tag{2}$$

where $a$ is the speed of sound. For an ideal gas, the speed of sound is given by

$$a = \sqrt{\gamma RT}\ . \tag{3}$$

where $\gamma$ is the specific heat ratio, $R$ is the specific gas constant, and $T$ is the gas temperature.

A one-dimensional *standing* acoustic pressure wave can be described by the expression

$$p'(x,t) = A(x)\sin\omega t\ . \tag{4}$$

where the **acoustic pressure** $p'$ sinusoidally fluctuates in time. $A(x)$ is the local amplitude of the pressure fluctuation at position $x$ along the length of the combustor, and $\omega$ is the fluctuation frequency (e.g., radians/second). Note that for this standing wave, *the spatial variation of the acoustic pressure is independent from the temporal variation*.

*Actually, this is true for the *fundamental* (axial) mode. The pipe can also resonate in harmonics of the fundamental mode (each having a frequency that is an integer multiple of the fundamental frequency).

Due to the boundary conditions at the ends of the pipe, the standing pressure wave has **nodes**, defined by $A(x)=0$, at the open ends of the pipe and an **anti-node**, a maximum amplitude, at the center of the pipe. It can be shown that the acoustic velocities are 90° out-of-phase with the acoustic pressures. Thus the velocity has a node at the pipe center and anti-nodes at the open ends.

As shown in Figure 1, the pressure and velocity amplitudes in the lower half of the tube are on the same side of the axis. In the upper part of the tube, on the other hand, they are on opposite sides. It can be shown that **if heat is added** 1) *in phase with the pressure oscillations* and 2) in a part of the tube *where velocity and pressure amplitudes are of the same sign*, the fluctuating heat release will drive the pressure oscillations. In other words, if heat is added near the middle of the lower half of the pipe the combustor will pulse. In a way this can be regarded as a cycle. The heat addition induces the pressure oscillations that in turn cause velocity oscillations. The pressure and velocity oscillations cause oscillations in heat release, which once again drive the pressure oscillations, and the cycle continues.

A schematic of the actual combustor is shown in Figure 2. The lower end of the tube is open to the atmosphere while the upper end connects, via a large decoupling chamber, to an exhaust pipe in the ceiling. The decoupler acts like a muffler while still simulating an open end at the top of the pipe. Quartz windows are fitted into the curved wall of the pipe around the center of the lower half of the Rijke tube. Through these the flame can be observed and the radiation measurements can be carried out. A propane-fired burner can be translated by remote control up and down inside the lower half of the tube. The position of the burner can be measured using a scale attached to the tube. The buoyancy produced by the hot combustion products causes an upward draft in the tube upon which the acoustic velocity fluctuations may be superimposed. The burner is ignited using a spark.

Three acoustic pressure transducers are fitted to the Rijke tube near its center and near the centers of the upper and lower halves of the tube (Figure 2a). An optical detector (photomultiplier) behind an interference filter is mounted opposite one of the windows. The outputs from the photomultiplier and the pressure transducers are amplified and can be connected either to an oscilloscope or a computer data acquisition system. The fuel flow rate is measured using a rotameter. The pressure in the flowmeter is measured using a pressure

gauge, while the temperature is assumed to be room temperature. Study Figure 2b and become familiar with it.

Instrumentation for Measurements

a) **Pressure Measurements** - The oscillating pressures in the pulse combustor will be measured using piezoelectric pressure transducers. This sensor portion of the transducer (Figure 3) is a small cylinder with a diaphragm on one end. The diaphragm covers a small piece of quartz or crystalline material. When the crystal experiences a stress on the diaphragm, it produces (or absorbs) *a current* that is proportional to the strain. This is known as the **piezoelectric effect**. The diaphragm is flush-welded to the case and acts as a cover for the crystal rather than as a sensing element. The output signal of the combined system is proportional to the strain, and thus the stress, applied on the crystal. For a piezoelectric pressure transducer, the stress is induced by the gas pressure on the diaphragm.

Thus piezoelectric sensor is something like the strain gages you used in previous labs, in that is also responds to strain. However it produces a current output, while a voltage is produced in an unbalanced strain gage bridge circuit. Electrically, the piezoelectric transducer resembles a capacitor, which can source or sink current. So, piezoelectric pressure sensors do not require an external excitation (i.e., power) source and are very rugged. The sensors however, do require charge amplification circuitry. Therefore the crystal output is connected to an electrostatic charge amplifier that generates a high level (millivolts), low impedance DC voltage output signal. The output signal is essentially the voltage drop $V$ across a resistor in the circuitry, i.e., $V=IR$, where $I$ is the amplified current and $R$ is the resistance.

These transducers have very fast response times (e.g., 1-10 μsec) and will, therefore, be able to follow the fluctuating pressure signals. However, they are also susceptible to shock/vibration induced strains, and they are very temperature sensitive. Thus we cannot mount them directly to the combustor wall, which will heat up during operation of the combustor. Instead, the transducers are mounted in a semi-infinite tube configuration shown in Figure 4. This removes the sensor from the hot wall. The long PVC tubing leading from the transducer to atmosphere prevents any pressure wave reflections from the end of the tube that may affect the frequency response of the transducer. Because the piezoelectric

transducers have a very rapid time response, we can connect them to time-resolved recording devices (e.g., oscilloscopes or computers) and generate power and phase spectra.*

b) **Reaction Rate Measurements -** The intensity of the combustion process, that is the rate at which fuel is consumed (the "reaction rate") and energy is released, can be monitored optically. During the combustion of hydrocarbon, the fuel reacts with the oxygen in the air to form carbon dioxide and water. However, this reaction does not occur in one step. Instead, a number of intermediates chemical species (radicals) are formed that have very short lifetimes before being destroyed in the next steps of the reaction process that lead to production of $CO_2$ and $H_2O$. Examples of these intermediates are OH, CH, H, O and HCO. Since these radicals have unpaired electrons ("unsatisfied bonds"), they tend to be unstable and react very quickly, a process during which they are consumed. It has been shown that much of the light emitted by a flame's reaction zone comes from radicals that are produced by a chemical reaction that leaves them with an electron in a high energy orbital. This high energy state tends to decay to a lower, equilibrium energy state through molecular collisions and, to a lesser extent, by emission of radiation (light). This process, chemical creation in an excited state followed by emission of light, is called **chemiluminescence**. The chemiluminescence is *roughly* proportional to the rate at which the reaction proceeds. Since the combustion process is exothermic, i.e., chemical bond energy is converted to thermal energy or heat, chemiluminescence is qualitatively proportional to the heat release rate (energy per unit time, i.e., power). A number of optical techniques have, therefore, been developed to detect flame radiation. These optical techniques also have the advantage that no foreign object, or probe, that would interfere with the chemical reaction by catalysis or quenching has to be introduced into the flame. Furthermore, these optical techniques have very fast response times.

The technique to be used here makes use of the fact that most of the radicals emit light in very specific ranges of wavelengths (or "colors"). In particular, OH chemiluminescence occurs mostly in the range 306-311 nm (1 nm = $10^{-9}$ m), which is in the ultraviolet region of the radiation spectrum. In our experiments, the fluctuations in heat release rate are measured

*A power spectrum is a graph of signal power (amplitude squared) versus frequency. Large single peaks indicate the signal is primarily composed of a single sine waves at the peak frequencies. The phase spectra shows the relative phase at each frequency.

by passing the light emitted by the flame through an interference filter onto a photomultiplier. The interference filter allows light only in a small band of wavelengths (around ~305-315 nm in our case) to pass while the photomultiplier converts this light into an electric current that can be measured. The interference filter consists of a quartz substrate, as opposed to standard glass that does not transmit ultraviolet light, on which a number of different, thin metallic coatings have been deposited in such a way as to reject all but the narrow range of wavelengths.

The photomultiplier consists of a photocathode, a series of charged screens or dynodes and an anode collector enclosed in an evacuated glass or quartz tube as shown in Figure 5. A high voltage (approximately 600 Volts) is applied between the cathode and anode while the dynodes are biased to intermediate voltages with a chain of resistors (the "dynode chain"). If photons are incident upon the photocathode, a proportional number of electrons are liberated (the **photoelectric effect**). These photoelectrons are then accelerated by the large voltage difference towards the (positive) anode. As these fast and accelerating electrons pass through or strike the dynodes, they liberate additional electrons that also accelerate towards the anode. After a number of dynodes, the original number of electrons has grown many times. Thus the original photons produce a small flow of electrons (a current!) that is amplified; hence the name photomultiplier. The number of electrons liberated per incident photon, which depends upon the work function of the cathode material, is referred to as the quantum efficiency $\eta$. In fact, the number of electrons emitted per photon is usually less than one, with $\eta$ often below 15%. The amplification factor depends upon the number of dynode stages (typically between 7 and 11) and the applied voltage. Together, they determine the overall gain of the photomultiplier tube. Since the work function of the cathode materials is wavelength (color) dependent, different tubes with different cathode materials are used for different applications. The output from the photomultiplier tube, which is a current, is passed through a resistor, and the resulting voltage (drop) is measured. As with the pressure data, the photomultiplier output can be connected to the oscilloscope or computer.

c) **Flow Measurements** - The fuel flow rate to the combustor will be measured using a rotameter type flow meter (Figure 6). It consists, basically, of a tapered glass (or plastic) tube held vertically with its larger end at the top. A float is free to move inside the tapered tube.

When a gas flows through the meter, the float will position itself at a given height. The fluid must then flow through the annular orifice between the float and the tapered tube. This orifice becomes larger as the float moves up the tube. This constriction causes the pressure below the float to be higher than that above, and the resulting force on the float, along with the upward force on the float due to buoyancy, must exactly balance the downward gravitational force on the float. Since an increase in flow rate requires an increase in orifice size in order to maintain a constant pressure difference across the float, the float will stabilize at a higher position in the tube as the flow rate increases. The position of the float can be read off an engraved scale on the tube wall. Frequently, two floats of different weights are included with the rotameter to extend its measuring range. Care must then be taken to assure that the lighter float is on top.

Rotameters must be calibrated. It can be shown that the flowrate-float position relationship for a given rotameter is dependent upon the densities of the gas and of the float. Therefore, it is necessary to know the temperature and pressure at which the flowmeter was calibrated as well as the conditions under which the flow meter is used. In addition, flow meters that are used for combustible gases are generally calibrated using air in order to avoid blowing combustibles into the laboratory. Finally, flow meter tubes may be calibrated using one float and then used with another of identical dimensions but different weight. It is, therefore, usually necessary to correct the measured flow rates for temperature, pressure, species and, sometimes, float material density. It can be shown that the following relationship can be used for this purpose (over some range of conditions).

$$Q = \frac{Q_{air\ fromcalib.curve}}{\left(\frac{14.7\,psia}{p_R}\right)^{1/2}\left(\frac{530°\mathrm{R}}{T_R}\right)^{-1/2}\left(\frac{SG}{1}\right)^{1/2}\left(\frac{SGF_1}{SGF2}\right)^{1/2}} \tag{3}$$

Here, $Q$ is the volumetric flowrate at **standard** conditions, 14.7 psi and 530 °R (for example, the units of $Q$ could be **standard** cubic centimeters per minute or SCCM), $p_R$ is the absolute pressure in the rotameter, $T_R$ is the absolute temperature in the rotameter, $SG$ is the specific gravity (with respect to air) of the gas whose flow rate is to be measured, $SGF_1$ is spec gravity of float used in the calibration and $SGF_2$ is the specific gravity of the float used in the actual measurement. Note that the above is the most general form of the rotameter correction. If, for example, the calibration chart furnished is already for the gas used, e.g., propane, that factor

is omitted. Care should be taken in using relationship (2) to convert air calibrated rotameters for use with very light gases like $H_2$. Finally, the temperature correction is generally small (since the calibration and operation temperatures are usually very close) and can, therefore, frequently be omitted.

## Safety Considerations

As with any combustion experiment **safety is a primary concern**. The fuel line is fitted with a manual shut off valve, pressure regulators and a remotely controlled solenoid valve. The fuel flow rate has been preset with the pressure regulators which are locked. Please **DO NOT** attempt to change their settings. The ignition circuit has been designed so as to switch on the solenoid valve and the spark simultaneously. This will prevent the build up of propane in the tube which might lead to an explosion. *If ignition does not occur within 10 seconds the system, including the fuel flow, will shut down*. Any propane remaining in the tube should then be flushed out with the compressed air provided **BEFORE** pushing the reset button and attempting to relight. An infrared detector mounted on the floor monitors the flame. If the flame is extinguished it will shut the solenoid valve in the fuel line. You may want to shut down the combustor by pushing the red button if you anticipate a longer delay between consecutive tests. The tube can get hot during operation, so **do not** touch it. Be sure to turn off all manual valves after all your tests are completed.

## Procedure

1. Determine the length of the Rijke tube, and the distances of the upper and lower pressure transducers from the central transducer.
2. Connect the upper (PU) and middle (PM) pressure transducers to the oscilloscope channels 1 and 2 (5 ms/div and 50 mV/div, set to AC coupling). The “Invert” button for channel 2 should be in the OUT position. Be sure that the thermocouple is retracted.

Flush the tube with air. Position the burner using the remote control so that you can see it through the upper part of the large window (at ~6" based on the scale attached to the combustor) and ignite by pushing the black button. Continue to hold down this button for ~5 seconds after ignition. Make sure the heavier float in the rotameter is at the correct position (190-200) and the gage pressure at the rotameter exit is near zero.

3. Observe the pressure traces corresponding to the upper (PU) and middle (PM) pressure transducers on the oscilloscope and take notes. Also observe and make notes about the flame shape. Is there a flame below the burner plate?
4. Now, lower the burner to the 0" station and repeat step 3.
5. Remove the PM transducer from the oscilloscope and replace it with the PMT output and change sensitivity to 2V/div. (AC coupling). Observe and compare the pressure and PMT traces.
6. Connect the pressure transducer and photomultiplier outputs to the four channels of the computer data acquisition system. Connect the sensors as follows:
   - channel #0 is the photomultiplier,
   - channel #1 is the upper pressure transducer (PU),
   - channel #2 is PM,
   - channel #3 is PL;
7. Acquire 1 or more data sets with the computer. Each time you acquire data, the computer will store the rms voltages, peak frequencies and associated phases for each of the channels. It will also store the power spectrum for each channel.
8. Open the valve at the back of the tube wall. Listen. Observe the flame and repeat step 7.
9. Close the valve and make sure the pulsations resume.
10. Raise the burner to the 2" station and repeat step 7.
11. Raise the burner <u>slowly</u> until the pulsations cease. Record the location where this happens and observe the flame shape when the pulsations cease. Repeat step 7.
12. Lower the burner <u>slowly</u> until the pulsations begin again. Record the location where this happens.
13. Shut down the burner using the stop button.

## Data To Be Taken

1. Rijke tube length and distance between pressure transducers.
2. Observations of the flame and transducer traces at the various burner locations described in the steps above.
3. Burner location where pulsations cease.
4. Computer data acquisition results at 0” (valve closed and open conditions), 2”, and pulsation cessation location.

## Data Reduction

1. Take the rms voltages corresponding to the three pressure signals as read by the computer and convert them to dB values (see “Conversions and Properties” section below). Use the attached calibration curve for all three transducers. The calibrations are similar enough for this to be close to correct.
2. Use the length of the Rijke tube to estimate its resonance frequency assuming the gas in the tube is air with a specific heat ratio of 1.4.
3. Determine the **relative** phase of the pressure and radiation signals by calculating difference between each signal and the signal from the middle pressure sensor (PM).

## Results Needed For Report

At a minimum, report the following results from the quantitative measurements that you carried out.

1. The frequencies and amplitudes (in dB) for the 3 pressure signals, and the frequency and rms of the PMT signal. At the four conditions (burner location and valve position) required in the Procedure. Include your estimated tube resonance frequency.
2. The relative phase angles of the peak frequencies of the three pressure signals and the PMT signal at the 0” burner location.

## Conversions and Properties

1. The sound pressure level (SPL) of an acoustic pressure field is given by

$$SPL(dB) = 20\log_{10}\left\{\frac{p_{RMS}}{p_{RMS_{threshold}}}\right\} \tag{2}$$

   where dB refers to **decibels**, $p_{RMS}$ is the root-mean-square fluctuation of the pressure field and $p_{RMS_{threshold}}$ is the nominal rms pressure fluctuation that corresponds to the "threshold of human hearing." This threshold value is standardized at $2\times10^{-4}$ dynes/cm$^2$ (or $2.0\times10^{-5}$ N/m$^2$=$2.0\times10^{-5}$ Pa=$2.9\times10^{-9}$ psi).

2. The heating value of propane is 2,563 BTU/SCF, where SCF is the **standard** cubic feet of propane, i.e., the volume of propane in ft$^3$ at **standard** conditions.

3. The calibration chart supplied for the flow meter was obtained for propane, that is the original calibration for air has already been corrected for the actual gas, propane, before plotting. In addition, you may assume the temperature correction is so small as to be negligible. However, the flow rate was calibrated using a glass float. The lower float used now is made of tantalon. In addition to the pressure calibration you must, therefore, now correct for the differences in float densities. The specific gravities of the floats are: $SG_{glass}$=2.98 and $SG_{tantalon}$=16.6.

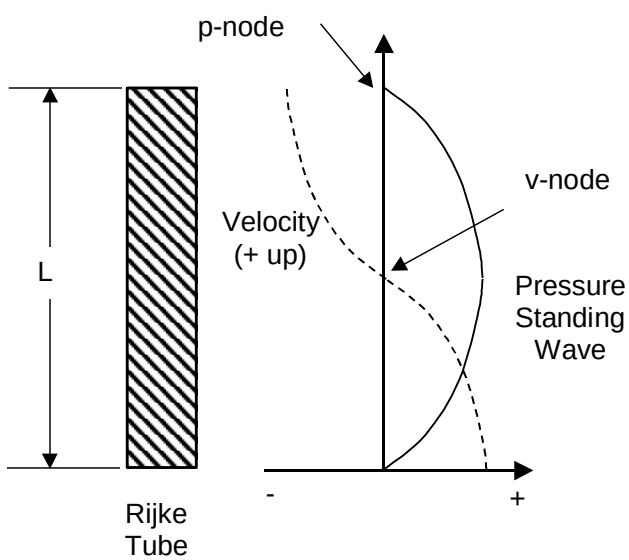
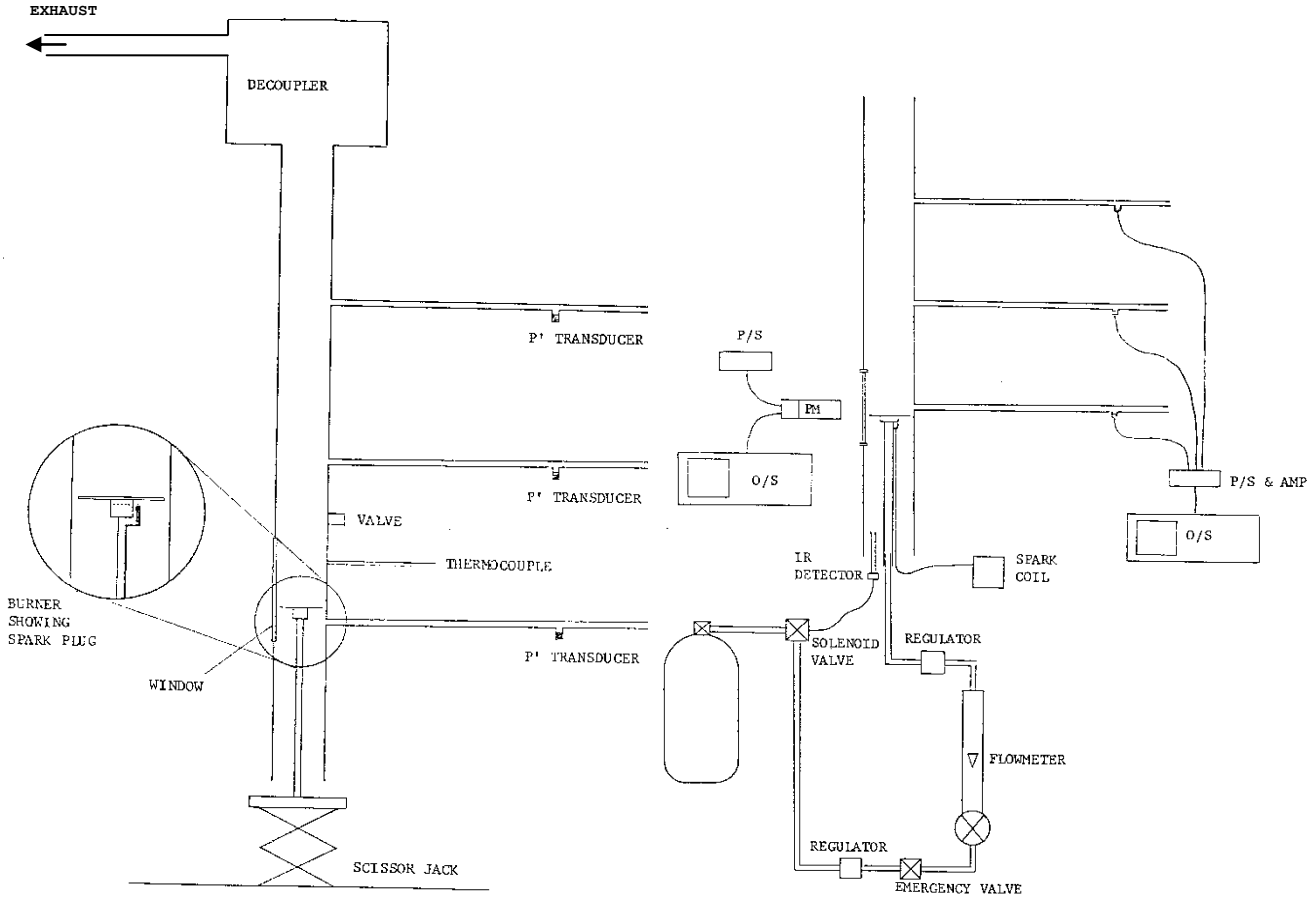



Figure 1. Schematic of standing wave in Rijke tube (note: the wavelength, $\lambda$=2L).




(a) (b)

Figure 2. RIJKE tube: (a) tube/combustor schematic, (b) hook-up schematic.

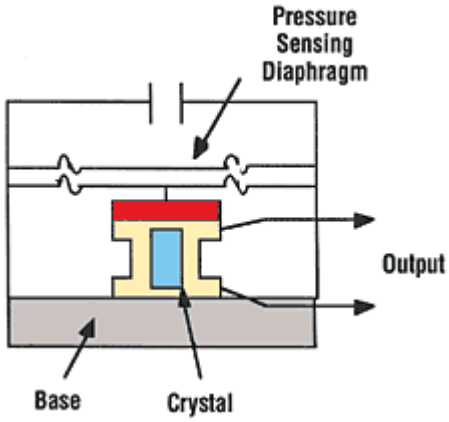



Figure 3. Schematic of piezoelectric pressure sensor (from "Pressure Measurement: Principles and Practice," sensorsmag.com/articles/0103/19/main.shtml).

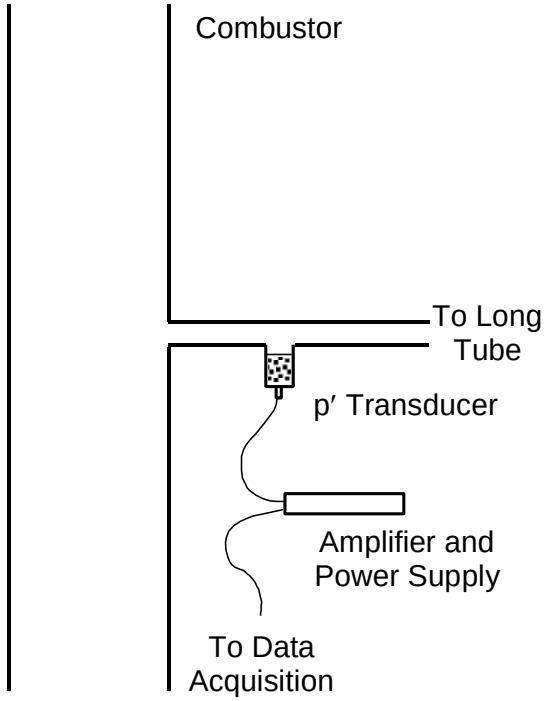



Figure 4. Schematic of pressure transducer mounted in semi-infinite tube configuration.

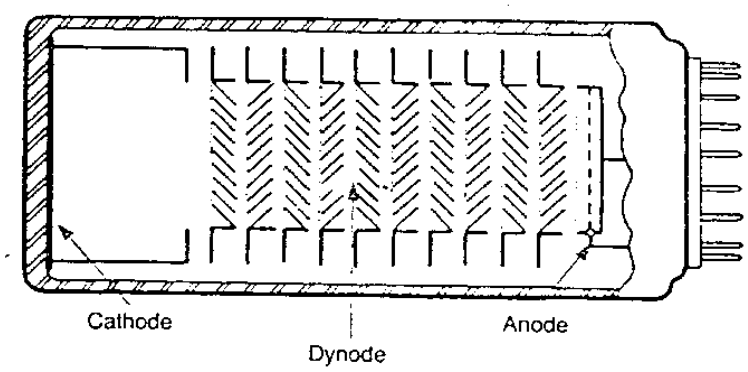



Figure 5. Schematic of photomultiplier.

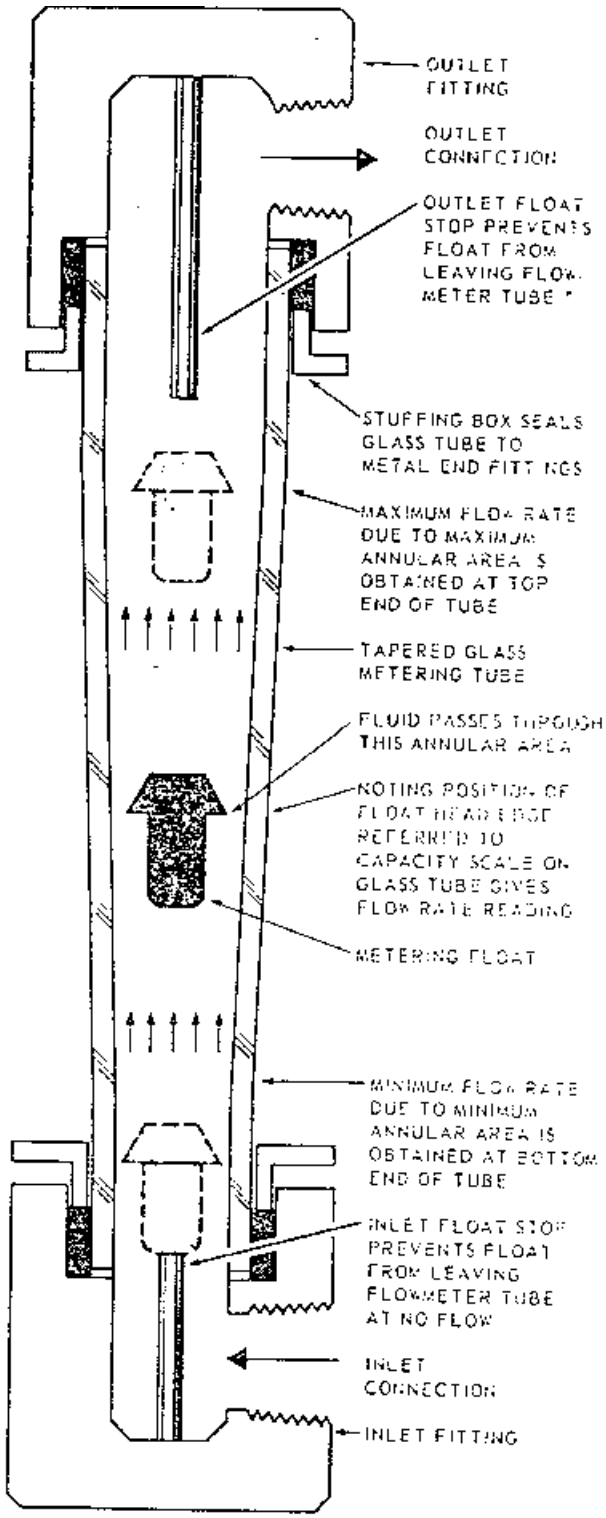



Figure 6. Schematic of rotameter type flow meter.

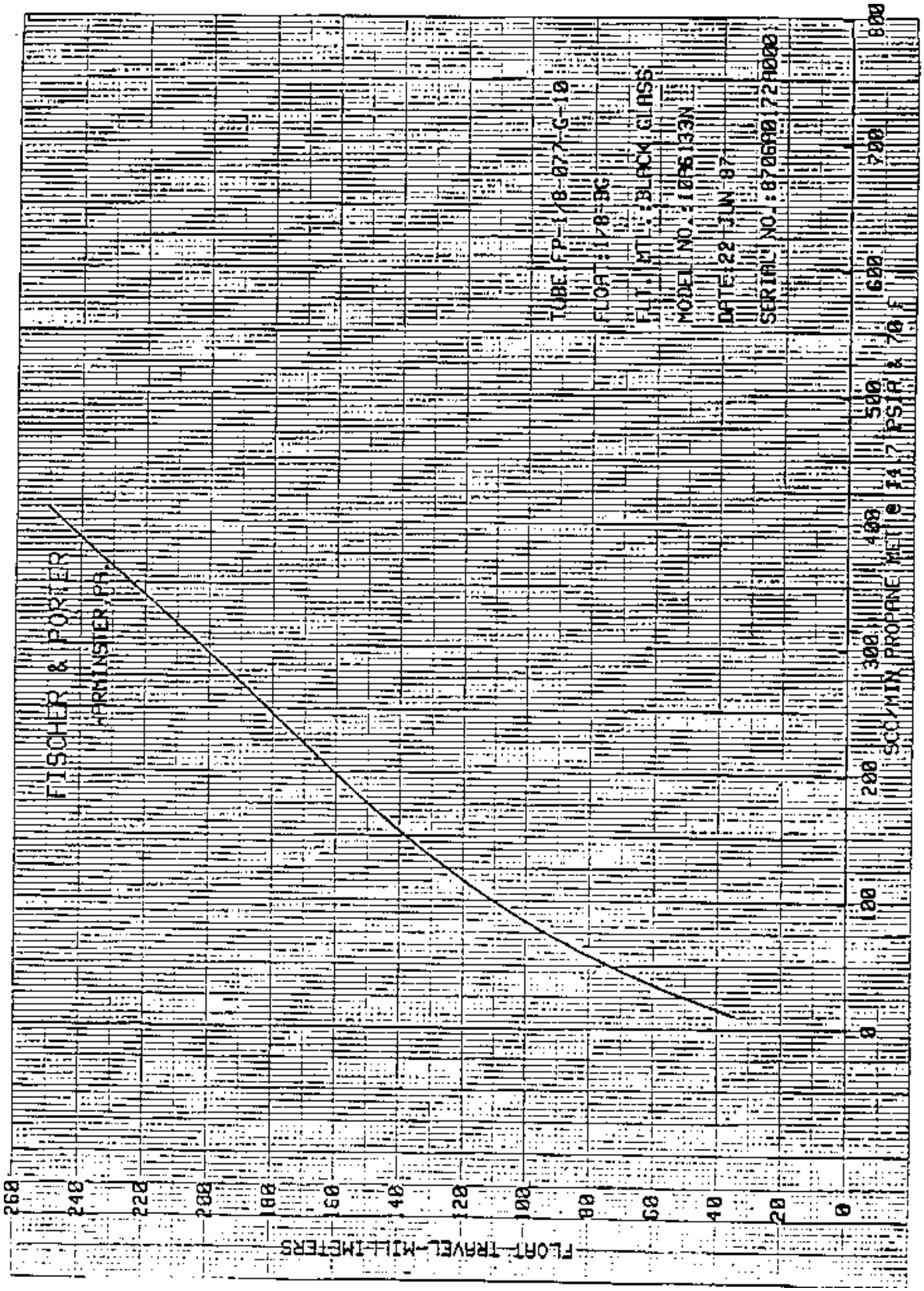



Figure 7 . Calibration curve for rotameter (propane).

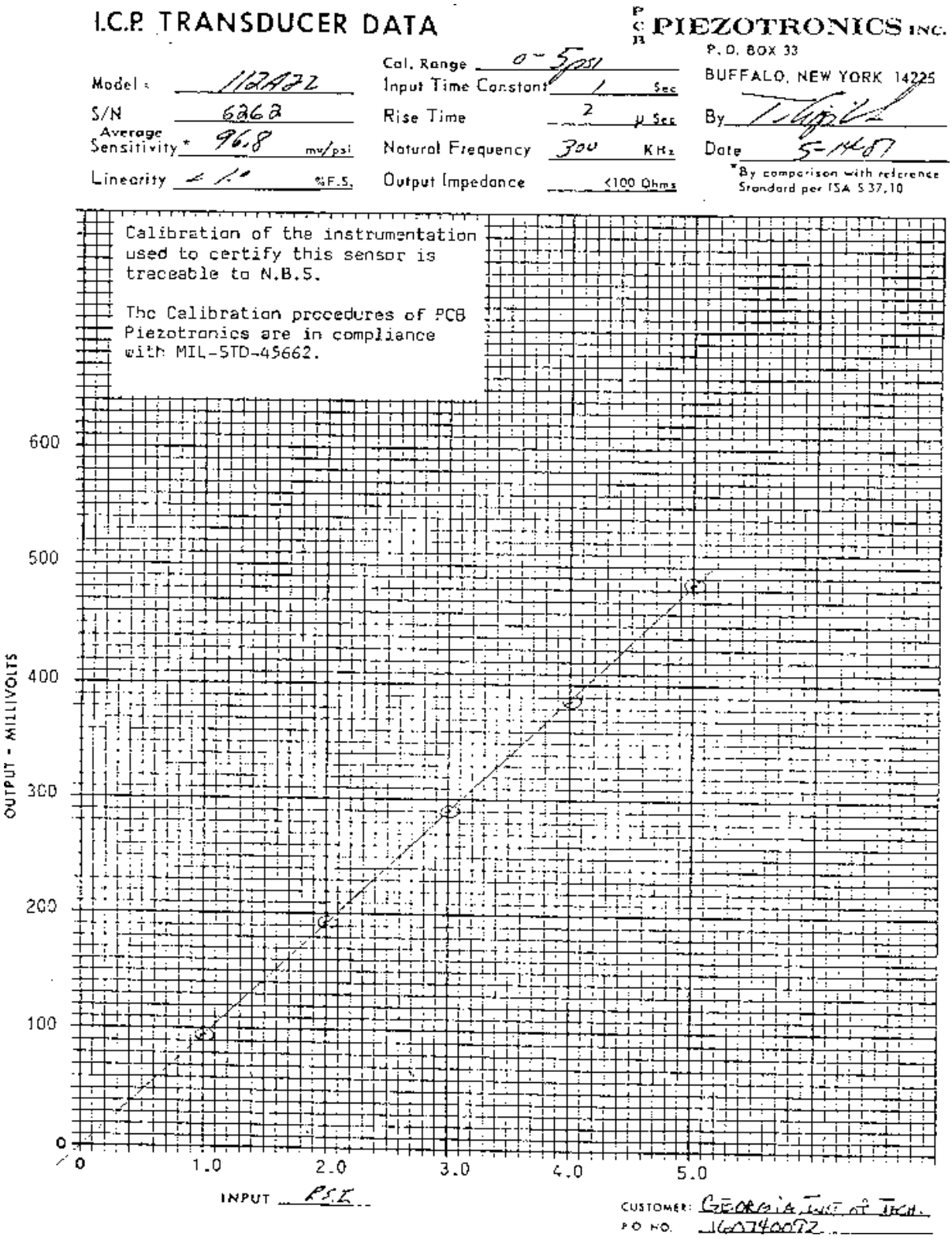



Figure 8. Calibration curve for piezoelectric transducer.