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**USE OF FLUIDIC OSCILLATOR
TO MEASURE FUEL-AIR RATIOS
OF COMBUSTION GASES**

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USE OF FLUIDIC OSCILLATOR TO MEASURE FUEL-AIR RATIOS OF COMBUSTION GASES

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SUMMARY

A fluidic oscillator was investigated for use in measuring fuel-air ratios in hydrocarbon combustion processes. Performance data for calibrating the fluidic oscillator were obtained from mixtures of nitrogen and carbon dioxide gas. To measure fuel-air ratios the oscillator was supplied with dry exhaust gas from an experimental combustor test rig burning ASTM A-1 jet fuel. Tests were conducted with fuel-air ratios between 0.015 and 0.031. The oscillator determined the ratios within 0.001 of the values computed from separate flow measurements of the air and fuel. It was concluded that fluidic oscillators have the potential for reliably measuring fuel-air ratios of combustors.

INTRODUCTION

Basic to all aircraft gas turbine propulsion systems is the transfer of energy to the working fluid by burning fuel in a combustion chamber. A wide variety of requirements make aircraft combustors and afterburners difficult to design. Some of these requirements are high rates of heat release, compact size, complete combustion, high air velocities, and controlled distributions of fuel and air. Inherent to the design and performance of an efficient system is a knowledge of the fuel-air distribution.

Methods for determining fuel-air ratio of a gas sample are generally elaborate. One method calculates the ratio from the amounts of carbon dioxide, carbon monoxide, and total unburned hydrocarbons in the dried gas sample. Amounts of carbon dioxide and carbon monoxide are determined from radiation absorption properties as measured with infrared analyzers. The hydrocarbons are measured with the flame ionization detector.

Other methods analyze the gas after it has been conditioned by a process that completely vaporizes, oxidizes, and dries it. For this conditioned gas there exists a single-value relation between its composition and the fuel-air ratio (ref. 1). Thus, fuel-air

ratio can be determined by measuring any property of the conditioned gas that can be correlated to its composition.

One such property of the conditioned gas is the speed of sound. One of the simplest devices for accurately measuring the acoustic properties of a gas is the fluidic oscillator. Fluidic oscillators are special whistles designed to produce sounds that correspond to certain properties of gases flowing through the instrument. They have been successfully used as molecular-weight sensors (ref. 2), temperature sensors (ref. 3), and humidity sensors for a hydrogen-steam mixture (ref. 4). The new application of using a fluidic oscillator for sensing fuel-air ratio was investigated at the NASA Lewis Research Center.

The fluidic oscillator under evaluation was operated with known gas mixtures to determine its operating characteristics. After calibration the oscillator was used to measure fuel-air ratios of an experimental combustor burning ASTM A-1 jet fuel. The combustor was a swirl-can full-annulus combustor approximately 1.1 meters in diameter. Tests were conducted with fuel-air ratios between 0.015 and 0.031.

SYMBOLS

a	free speed of sound
b	algebraic constant
c	wave propagation velocity
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
f/a	fuel-air ratio
f	algebraic function
H/C	hydrogen-carbon mass ratio
k	oscillator calibration constant
L	actual oscillator feedback path length
\mathcal{L}	effective oscillator feedback path length
M	molecular weight
m	mass
n	amount of excess air
P	period of oscillator cycle
R	gas constant

- \mathcal{R} universal gas constant
- T temperature
- t_r transport time component of oscillator period
- t_s switching time component of oscillator period
- z constant relating wave propagation velocity to free speed of sound
- γ ratio of specific heats

THEORY

Fluidic oscillators are sinusoidal pressure generators originally developed for timing applications and for sensing temperatures and pressures in fluidic control systems. Their operating characteristics depend primarily on the type of feedback employed to maintain pressure oscillations. Reviews of some basic designs and applications are given in references 5 and 6.

The particular type of oscillator that was investigated for use in measuring fuel-air ratios in hydrocarbon combustion processes is shown schematically in figure 1. Its operation is based on the fact that the inlet flow is easily deflected by a small pressure difference between the two control ports. A change in inlet flow direction increases the pressure in one receiver port and decreases the pressure in the other receiver port. This change produces a compression wave in one feedback duct and a rarefaction wave in the other feedback duct. When these pressure waves arrive at the control ports, they divert the inlet flow towards the other receiver. The result is a device in which the inlet flow oscillates between the two receiver ports.

The analysis of this oscillator is given in detail in appendix A. The output frequency is shown to be directly related to the speed of sound when flow velocities are held constant by choked conditions. The speed of sound can be defined in terms of gas temperature, ratio of specific heats, and molecular weight of the fluid. The following equation then results for the output frequency:

$$\text{frequency} = k \sqrt{T} \sqrt{\frac{\gamma}{M}} \quad (1)$$

where k is the calibration constant associated with oscillator size.

Use of the oscillator in this application requires that a particular fuel-air ratio results in a unique γ/M ratio for the combustion products. A single-value relation between composition and fuel-air ratio can be obtained by completely vaporizing, oxidizing, and drying the gas sample (ref. 1). This relation is derived in appendix B. The result

can be expressed in the following form:

$$\sqrt{\frac{\gamma}{M}} = f\left(\frac{H}{C}, \frac{f}{a}, T\right) \quad (2)$$

Figure 2 shows the relation between γ/M of a conditioned sample and the fuel-air ratio for a fuel with a hydrogen-carbon mass ratio of 0.17 and a temperature of 293 K (68° F). The value of γ/M changes about 7 percent across the range from zero f/a to stoichiometric. According to equation (1), this range will change the oscillator frequency by approximately 3 percent.

Thus, oscillator frequency can be related to fuel-air ratio by the following relation, obtained by combining equations (1) and (2):

$$\text{frequency} = k \sqrt{T} f\left(\frac{H}{C}, \frac{f}{a}, T\right) \quad (3)$$

APPARATUS AND TEST PROCEDURE

The objective was to explore the possibility of using a fluidic oscillator to measure fuel-air ratios. Two sets of tests were performed. The first used known gas mixtures to check the validity of equation (1), measure the calibration constant k , and evaluate the effects of pressure on the oscillator frequency. The second set of tests used samples of combustor exhaust gas to confirm the validity of equation (3).

Figure 3(a) shows a schematic of the test apparatus used to calibrate the oscillator. Pressure conditions were controlled by a pressure regulator in the gas supply line and a bypass valve. The oscillator exhausted to the atmosphere. Operating pressures were monitored with a gage connected to the line upstream of the oscillator inlet. Temperature was controlled by passing the sample line through a heated water bath. The sample temperature was limited to the range 283 to 330 K. A thermocouple just upstream of the oscillator inlet was used to measure the sample gas temperature.

A piezoelectric pressure transducer was used to detect the pressure oscillations in one of the two feedback ducts. The transducer output signal was a modified sine wave whose frequency was measured by a digital frequency counter that displayed the total number of cycles counted in a 1-second period.

The oscillator was calibrated with nitrogen and carbon dioxide. Mixtures of 0, 8, 10, 16, 70, and 100 percent (by volume) carbon dioxide in nitrogen were used. The procedure consisted of selecting a gas mixture, maintaining a constant sample temperature, and varying pressure conditions. The results provided the value for k .

The apparatus was then modified and connected to a sampling probe in an experimental combustor burning ASTM A-1 jet fuel which has a hydrogen-carbon ratio of 0.17. The combustor was an annular design approximately 0.5 meter long and 1.1 meters in diameter. It contained 120 swirl-can modules which distributed combustion uniformly across the annulus.

The major change to the apparatus was the addition of a desiccant drier that removed water vapor from the combustion products being sampled. The water-bath heater was not used during this part of the test but was retained to ensure that the sampling line was sufficiently long to allow the gas to cool to ambient temperature before passing through the oscillator. A single-point sampling probe and a seven-point sampling probe were used. The combustion-gas sampling system is shown schematically in figure 3(b).

Prior testing had established the fact that the combustor operated near 100 percent efficiency at the range of fuel-air ratios tested. Consequently, for this experiment an oxidizer was not deemed necessary.

RESULTS AND DISCUSSION

Gas pressure and temperature conditions had considerable effects on oscillator performance and had to be taken into account. The sensitivity of the oscillator to changes in pressure ratio across the oscillator is shown in figure 4. The oscillator was exhausted to the atmosphere for these data. Data for pressure ratios below 1.2 are not presented because the sensitivity of the frequency detector system was insufficient to yield consistent results. As can be seen in figure 4, frequency increased with pressure ratio until a pressure ratio of about 3 was reached.

Constant frequencies for pressure ratios above 3 can be explained by considering the oscillator as being similar to two orifices in series. The first orifice would represent the inlet nozzle, and the second orifice would have the combined areas of the two exhaust ports (see fig. 1). The exhaust ports choke first with a pressure ratio of about 1.9, the theoretical critical pressure ratio. At this time the pressure ratio across the inlet nozzle is about 1.7, so that the overall pressure ratio is about 3.2. When the outlet orifice is choked, the fluid velocities in the inlet nozzle and passageway remain constant and independent of supply pressure (ref. 7). Consequently, the oscillator frequency becomes insensitive to inlet and exhaust pressures for pressure ratios greater than 3.2.

The effect of temperature is illustrated in figure 5, where oscillator frequency is shown as a function of the square root of the absolute temperature of the gas sample. From equation (1) it can be seen that frequency is a linear function of the square root of temperature if the gas composition is constant. Although there is data scatter, figure 5 substantiates this relation. The scatter resulted primarily from temperature gradients

between the temperature measurement station and the oscillator inlet and the lack of precision in the temperature readout system.

Figure 6 presents oscillator calibration constants that were computed from equation (1) for different gas samples. The data in figure 6 were obtained from combustion tests and calibration tests for oscillator pressure ratios above 3.2. Values of γ/M for combustion products were computed from airflow and fuel-flow measurements by using the procedure given in appendix B. An intermediate value of 758.00 was selected as the best fit to figure 6. The maximum range of k was within ± 0.5 percent of 758.00.

The experimentally determined k was then used to generate theoretical curves that define fuel-air ratio in terms of oscillator output frequency. Figure 7 shows the theoretical curves and test data for several temperatures. Good agreement is shown by the small horizontal deviation of the data from the curves.

Fuel-air ratios were also determined from measurements of airflow and fuel flow. A comparison of flow-determined and oscillator-determined ratios is shown in figure 8. The data lay in a band bounded by lines having a slope of unity. Thus, the deviation remained constant at ± 0.001 over the range of fuel-air ratios examined. This deviation is considered reasonably good in consideration of the fact that the flow-determined values represent average values, while the oscillator gave answers based on single- or multiple-point sampling. Other sources of experimental errors are (1) effects of small changes and measurement errors in gas sample temperature, (2) sensitivity of the frequency detection system, and (3) the assumption of complete combustion in the experimental combustor.

Because of the coarseness of the 2° F graduations of the temperature readout meter, the sample temperature could be read only to the nearest 0.3 K (0.5 $^{\circ}$ F). A 0.3 K error in gas temperature measurement would result in approximately a 0.0005 error in fuel-air ratio, or 50 percent of the scatter band.

The frequency detection system used in this test was precise to 1 hertz. A difference of 1 hertz results in approximately 50 percent of the scatter band in figure 8.

The complete combustion assumption was substantiated by chemical analysis of gas samples taken simultaneously with the single-point probe. Chemical analysis gave the following results:

Component	Concentration, ppm
Unburned hydrocarbons	300
Carbon monoxide	1000 to 2500
Nitrogen oxide	10 to 80

The effect of these levels on oscillator frequency resulted in a 0.0001 error in fuel-air ratio, or approximately 10 percent of the scatter band.

CONCLUDING REMARKS

An investigation using exhaust-gas samples showed that fluidic oscillators have the potential for giving accurate fuel-air-ratio information over the normal operating range of a combustor. For accurate results the sample had to be properly conditioned, the oscillator had to be run at a high pressure ratio, and the sample temperature had to be accurately measured.

In this investigation the gas was conditioned by removing only water vapor. This conditioning was sufficient because the combustor was highly efficient, and only low fuel-air ratios were used. Richer mixtures may produce levels of carbon monoxide and unburned hydrocarbons that would make the oscillator prediction meaningless unless they were removed from the sample by oxidation. Therefore, the oscillator support equipment should include some type of processing device that ensures a completely oxidized sample.

The oscillator used in this investigation had the disadvantage of requiring a high pressure ratio to make the output insensitive to changes in supply pressure. A different oscillator design with lower choking pressure ratio and lower flow consumption would be more practical. Any new oscillator used for analyzing gas should be self-purging so that the output could respond rapidly to changes in gas composition.

Accurate temperature measurement of the gas inside the oscillator is most important for accurately determining the fuel-air ratio. A temperature probe with an accuracy of 0.3 K (0.5° F) located in the supply line close to the oscillator was barely adequate. A better system would have the probe located just upstream of the inlet nozzle and have an accuracy of 0.05 K.

Several prepared gas mixtures were used to calibrate the oscillator. This procedure is generally not necessary for obtaining good calibration. Any known gas, other than a monatomic gas such as helium (ref. 2), should give equally good calibration. An especially suitable calibration mixture would be dry air, for it establishes the zero-fuel-air-ratio condition directly.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 4, 1974,
501-24.

APPENDIX A

RELATING OSCILLATOR FREQUENCY TO FLUID PROPERTIES

Tests showed that the fluidic oscillator schematically illustrated in figure 1 acted as a differential amplifier with delay-line negative feedback. In operation, a portion of the inlet flow switches back and forth between the two receiver ports. This oscillation is maintained by signals that propagate around the feedback loop at local sonic velocity. The frequency of oscillation depends on the transport time (the time in which the signal traverses the feedback loop) and the switching time lag.

The transport time is

$$tr = \frac{L}{c} \quad (A1)$$

where c is the wave propagation velocity, and L is the feedback path length. Note that the feedback path starts at the inlet nozzle (fig. 1) and follows the passageway around to and through the feedback duct back to the inlet. The wave propagation velocity is a function of the fluid velocity, line resistance, line inertance (a function of passage geometry), frequency, and free speed of sound a . For this oscillator operating with choked flow in the exhaust ports, c can be considered proportional to a , or

$$c = za \quad (A2)$$

where z is some constant.

The transport time can then be expressed as

$$tr = \frac{L}{za} = \frac{\mathcal{L}}{a} \quad (A3)$$

where

$$\mathcal{L} = \frac{L}{z} \quad (A4)$$

A standard equation for the free speed of sound a is

$$a = \sqrt{\gamma \frac{g}{M} T} \quad (A5)$$

where \mathcal{R} is the universal gas constant, M the molecular weight, γ the ratio of specific heats, and T the temperature. The transport time then becomes

$$tr = \frac{\mathcal{L}}{\sqrt{\gamma \frac{\mathcal{R}}{M} T}} = \frac{\mathcal{L}}{\sqrt{\mathcal{R}}} \sqrt{\frac{M}{\gamma T}} \quad (\text{A6})$$

The switching time, or the time lag associated with the deflection of the inlet jet (ref. 2) is

$$t_s = k_1 \sqrt{\frac{M}{\gamma T}} \quad (\text{A7})$$

where k_1 is some constant. The period P of one complete cycle is

$$P = 2(t_r + t_s) = 2 \left(\frac{\mathcal{L}}{\sqrt{\mathcal{R}}} \sqrt{\frac{M}{\gamma T}} + k_1 \sqrt{\frac{M}{\gamma T}} \right) \quad (\text{A8})$$

or

$$P = k_2 \sqrt{\frac{M}{\gamma T}} \quad (\text{A9})$$

where

$$k_2 = 2 \left(\frac{\mathcal{L}}{\sqrt{\mathcal{R}}} + k_1 \right) \quad (\text{A10})$$

Thus, the frequency of oscillation is

$$\text{frequency} = k \sqrt{T} \sqrt{\frac{\gamma}{M}} \quad (1)$$

where

$$k = \frac{1}{k_2} \quad (\text{A11})$$

As derived in appendix B,

$$\sqrt{\frac{\gamma}{M}} = f\left(\frac{H}{C}, \frac{f}{a}, T\right) \quad (2)$$

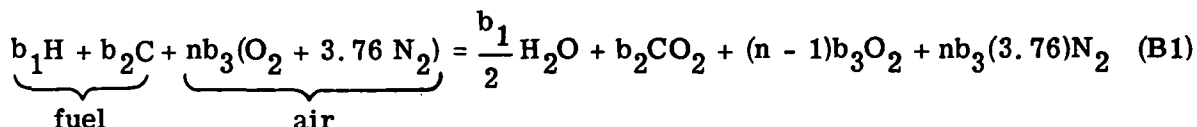
Thus,

$$\text{frequency} = k \sqrt{T} f\left(\frac{H}{C}, \frac{f}{a}, T\right) \quad (3)$$

APPENDIX B

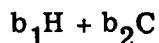
RELATING COMBUSTION PRODUCTS TO FUEL-AIR RATIO

If the fuel burned is assumed to be a hydrocarbon fuel having no impurities, the generalized combustion equation (ref. 8) can be written in algebraic form as follows:



where b_1 , b_2 , and b_3 are algebraic constants, and n is the amount of excess air. This equation assumes complete combustion of the fuel.

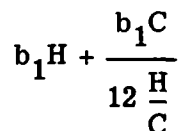
Since fuels such as jet engine fuel are mixtures of hydrocarbon compounds, it was necessary to break down these compounds into carbon and hydrogen and create a dummy fuel "molecule":



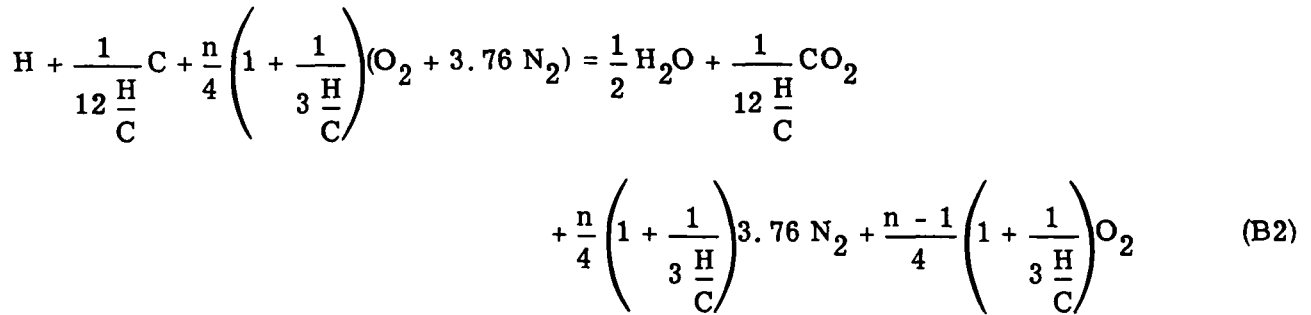
If the hydrogen-carbon mass ratio of the fuel is H/C and the mass of hydrogen present in one "molecule" is the constant a , the number of carbon atoms present in the "molecule" is

$$\frac{b_1}{12 \frac{H}{C}}$$

and the fuel can be represented by



(For the purpose of this discussion approximate values for molecular weights are as follows: hydrogen (H_2), 2; carbon (C), 12; nitrogen (N_2), 28; oxygen (O_2), 32.) The combustion equation becomes



For stoichiometric burning, $n = 1$. The stoichiometric fuel-air ratio is

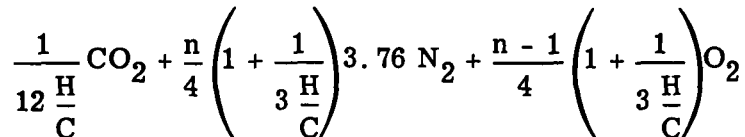
$$\left(\frac{f}{a} \right)_{\text{stoich}} = \frac{\text{mass fuel}}{\text{mass air}} = \frac{1 + \frac{1}{3} \frac{\text{H}}{\text{C}}}{34.32 \left(1 + \frac{1}{3} \frac{\text{H}}{\text{C}} \right)} \quad (\text{B3})$$

For burning with excess air, the amount of excess air n is

$$n = \frac{\left(\frac{f}{a} \right)_{\text{stoich}}}{\frac{f}{a}} = f \left(\frac{\text{H}}{\text{C}}, \frac{f}{a} \right) \quad (\text{B4})$$

where f/a is the fuel-air ratio.

If the water is removed, the remaining combustion products are



The mass of the dry products m is

$$m = \frac{44}{12} \frac{\text{H}}{\text{C}} + \frac{n}{4} \left(1 + \frac{1}{3} \frac{\text{H}}{\text{C}} \right) (3.76)(28) + \frac{n-1}{4} \left(1 + \frac{1}{3} \frac{\text{H}}{\text{C}} \right) (32) = \frac{11.44 n + 1}{\frac{\text{H}}{\text{C}}} + 34.32 n - 8 \quad (\text{B5})$$

The molecular weight and ratio of specific heats for the dry products can be determined by treating the products as a nonreactive mixture and applying the Gibbs-Dalton law (ref. 8). The molecular weight M of a nonreactive mixture of three gases is

$$M = \frac{m}{\frac{m_1}{M_1} + \frac{m_2}{M_2} + \frac{m_3}{M_3}}$$

where the terms with subscripts refer to the constituent gases, and the terms without subscripts refer to the total mixture. The specific heat at constant volume for the mixture is

$$c_v = \frac{m_1 c_{v1} + m_2 c_{v2} + m_3 c_{v3}}{m} \quad (\text{B7})$$

The specific heat at constant pressure for the mixture is

$$c_p = \frac{m_1 c_{p1} + m_2 c_{p2} + m_3 c_{p3}}{m} \quad (\text{B8})$$

The ratio of specific heats for the mixture is

$$\gamma = \frac{c_p}{c_v} \quad (\text{B9})$$

In order to apply these expressions to the dry products of combustion, it is necessary to know the specific heats and molecular weights of the gases making up the mixture. It is also necessary to find the mass of each gas present in the mixture. The different terms in equation (B5) give the masses of the constituents:

$$\left. \begin{aligned} m_{\text{CO}_2} &= \frac{44}{12 \frac{\text{H}}{\text{C}}} \\ m_{\text{N}_2} &= \frac{n}{4} \left(1 + \frac{1}{3 \frac{\text{H}}{\text{C}}} \right) (3.76) (28) \\ m_{\text{O}_2} &= \frac{n-1}{4} \left(1 + \frac{1}{3 \frac{\text{H}}{\text{C}}} \right) (32) \end{aligned} \right\} \quad (\text{B10})$$

Substituting these expressions into equation (B6) and (B9) will result in expressions for evaluation of molecular weight and ratio of specific heats for the dry products of combustion. Therefore,

$$\sqrt{\frac{\gamma}{M}} = f\left(\frac{H}{C}, \frac{f}{a}, T\right) \quad (2)$$

where T is the temperature of the gas and is included because the numerical values of the specific heats depend on the temperature of the gas.

To demonstrate the computation procedure, the value of γ/M will be determined for dry combustion products at 293 K for a fuel with a hydrogen-carbon ratio of 0.17 and a fuel-air ratio of 0.020. Equation (B3) gives

$$\left(\frac{f}{a}\right)_{\text{stoich}} = \frac{1 + \frac{1}{0.17}}{34.32 \left(1 + \frac{1}{3(0.17)}\right)} = 0.0677$$

From equation (B4),

$$n = \frac{0.0677}{0.0200} = 3.3850$$

From equation (B5),

$$m = \frac{11.44(3.3850) + 1}{0.17} + (34.32)(3.3850) - 8 = 341.846$$

Equation (B10) gives the component masses:

For CO_2 :

$$m_{\text{CO}_2} = \frac{44}{12(0.17)} = 21.5686$$

For N_2 :

$$m_{\text{N}_2} = \frac{3.3850}{4} \left[1 + \frac{1}{3(0.17)}\right] (3.76)(28) = 263.786$$

For O₂:

$$m_{O_2} = \frac{(3.3850 - 1)}{4} \left[1 + \frac{1}{3(0.17)} \right] (32) = 56.4918$$

As a check, $m_{CO_2} + m_{N_2} + m_{O_2} = m$. Equation (B6) gives the mean molecular weight of the dry products of combustion:

$$M = \frac{341.846}{\frac{21.5686}{44} + \frac{263.786}{28} + \frac{56.4918}{32}} = 29.277$$

At 293 K (68° F) the specific heats at constant pressure are

$$c_{p, CO_2} = 37.155 \text{ J/(g mole)(K)}$$

$$c_{p, N_2} = 29.142 \text{ J/(g mole)(K)}$$

$$c_{p, O_2} = 29.397 \text{ J/(g mole)(K)}$$

and

$$R = 8.320 \text{ J/(g mole)(K)}$$

From equation (B8),

$$c_p = \frac{(21.5686)(37.155) + (263.7857)(29.142) + (56.4918)(29.397)}{341.8461} = 29.689$$

Since $c_v = c_p - R$,

$$\gamma = \frac{c_p}{c_p - R}$$

and

$$\frac{\gamma}{M} = 0.0474$$

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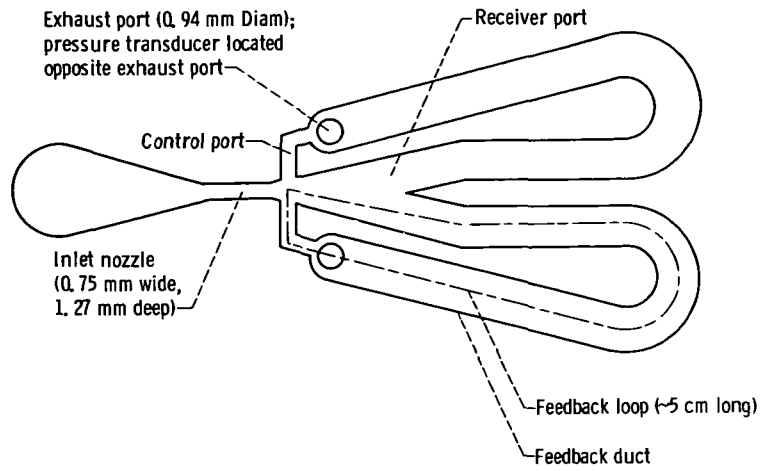


Figure 1. - Schematic of fluidic oscillator. (Not to scale.)

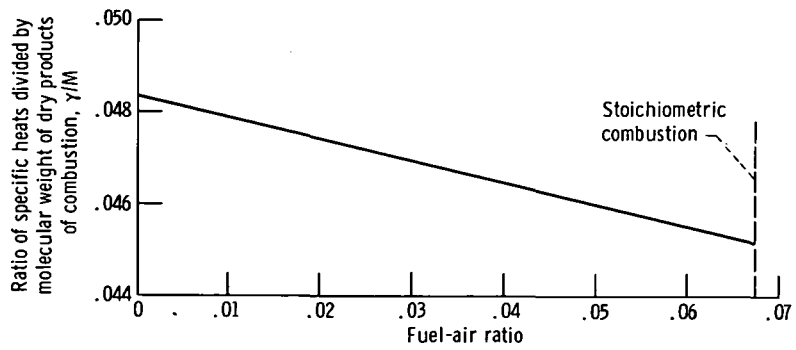
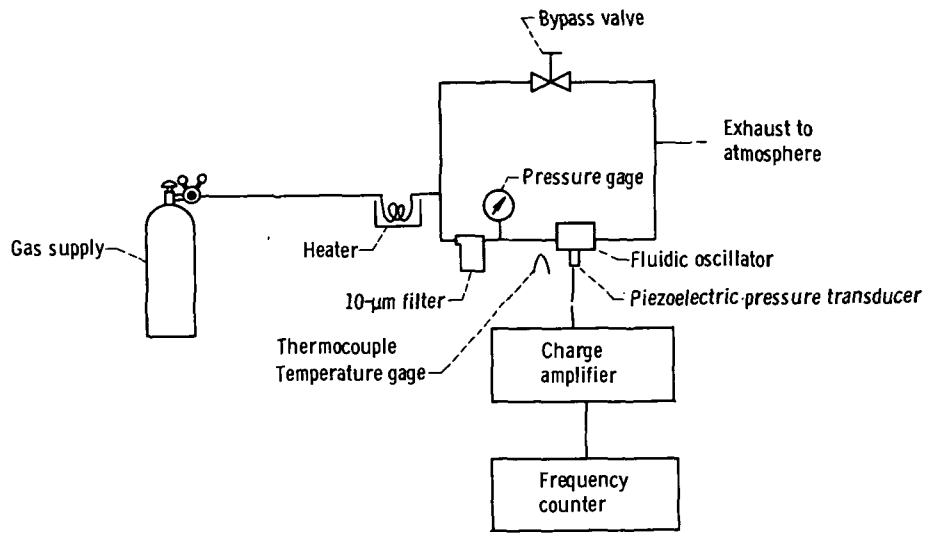
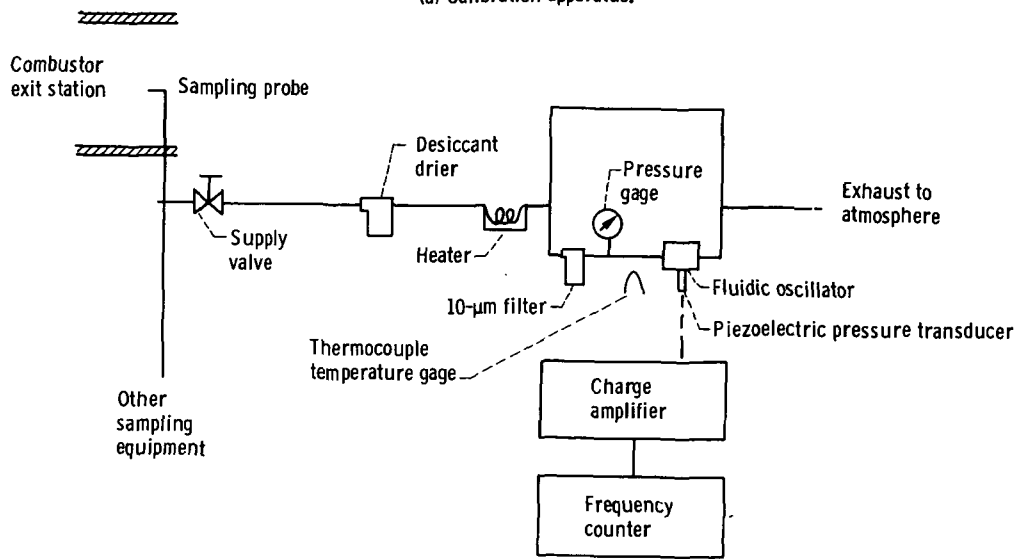


Figure 2. - Ratio of specific heats divided by molecular weight of dry products of combustion as function of fuel-air ratio. Fuel hydrogen-carbon ratio, 0.17; temperature, 20^o C (68^o F).



(a) Calibration apparatus.



(b) Combustion-gas sampling apparatus.

Figure 3. - Schematic of test apparatus.

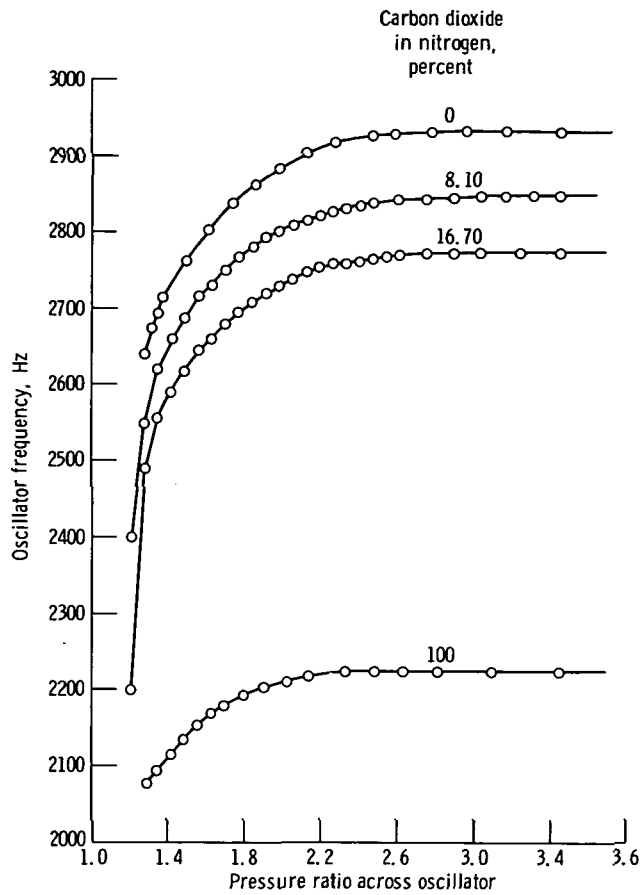


Figure 4. - Effect of pressure ratio on oscillator performance. Sample exhausted to atmosphere; sample gas temperature, 300 K.

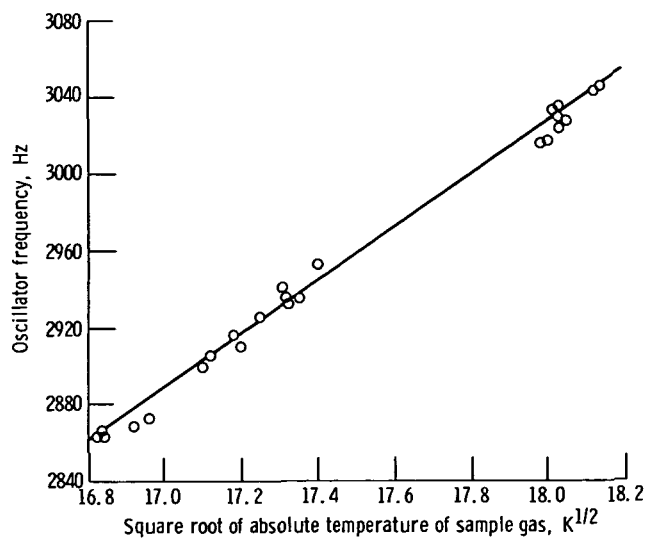


Figure 5. - Typical effects of gas temperature on oscillator operation. Nitrogen gas at choked operation.

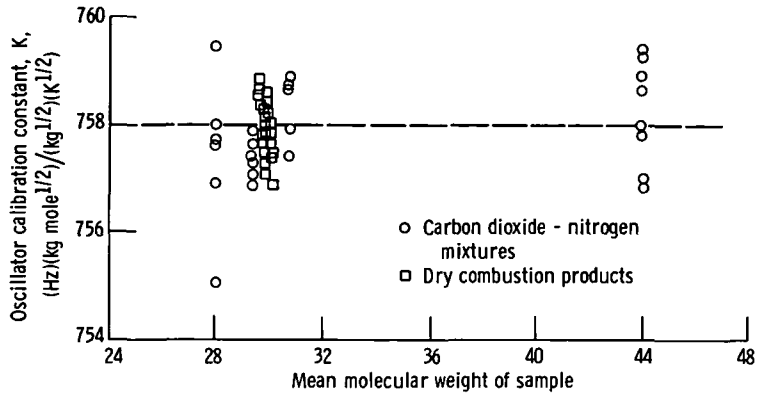


Figure 6. - Oscillator calibration constant as function of sample gas mean molecular weight.

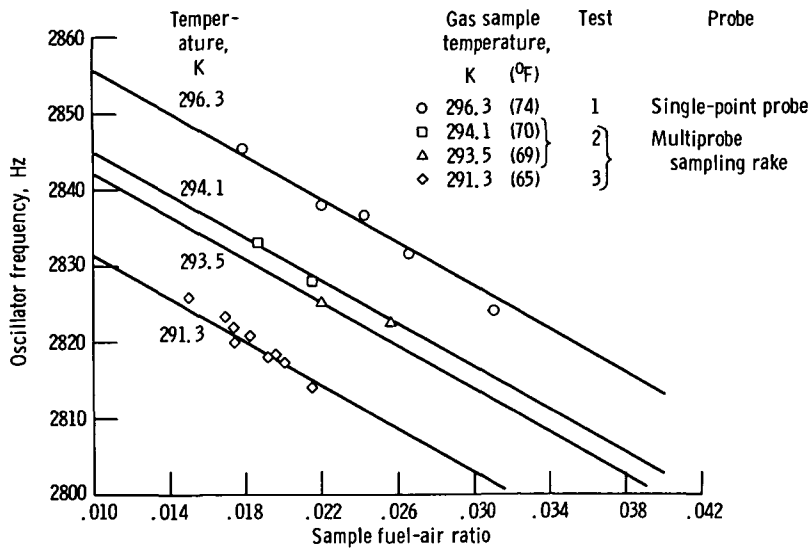


Figure 7. - Oscillator performance for combustion of ASTM A-1 jet fuel.

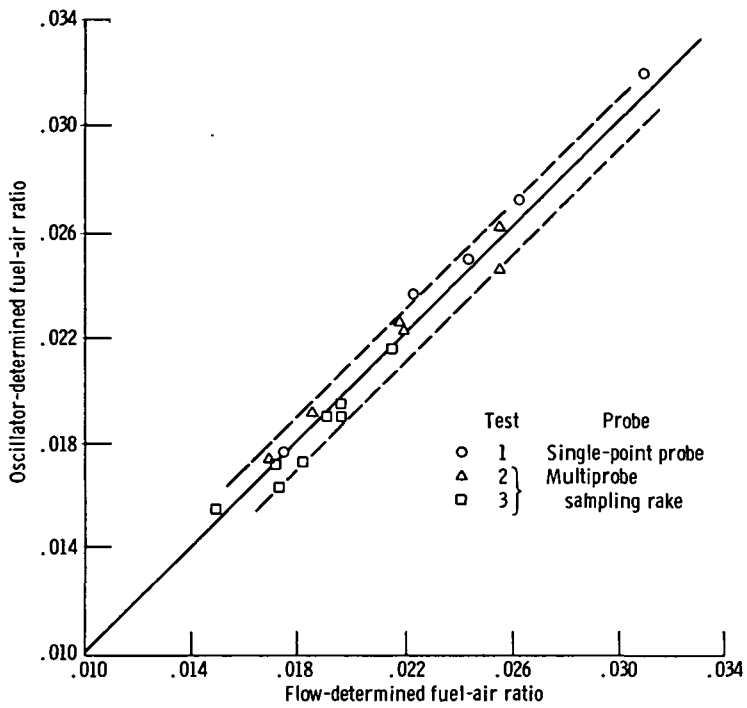


Figure 8. - Oscillator-determined fuel-air ratios compared to flow-determined fuel-air ratios.



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