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SENSING MOLECULAR WEIGHTS OF GASES WITH A FLUIDIC OSCILLATOR

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Cleveland, Ohio

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16. Abstract

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SUMMARY

A fluidic oscillator was investigated for use as a molecular-weight sensor of gases. Data were taken using monatomic and polyatomic gases having molecular weights from 4 to 83.8. From test results, it was observed that for choked flow or constant pressure drop the oscillator frequency is proportional to the sonic velocity in the medium but the monatomic and polyatomic gases have a different constant of proportionality. The effect of changes in pressure drop and temperature on oscillator frequency is also discussed.

INTRODUCTION

Gas mixtures are being used as the working fluid in closed Brayton-cycle systems for space power generation (ref. 1). Small changes in the molecular weight of the gas mixture can cause significant changes in operating characteristics of turbomachinery and overall system performance. To monitor molecular weight continuously, reference 2 suggests the use of a bistable fluidic oscillator. Fluidic oscillators and their operating principles are described in references 3 and 4.

An experimental investigation was performed to examine a fluidic oscillator to sense molecular weight of flowing gases having molecular weights from 4 to 83.8. Data were taken using four monatomic gases (helium, neon, argon, and krypton), as well as five polyatomic gases (carbon dioxide, air, nitrogen, propane, and methane). Testing was done in two phases. In phase 1, the oscillator was tested using each of the nine gases at ambient temperature over a range of oscillator pressure drop. Pressure drop was increased until output frequency became constant. These pressure drops were less than 30 psi (21 N/cm^2) at atmospheric exhaust for all the gases used. In phase 2, the oscillator was tested using nitrogen, carbon dioxide, and argon over a range of temperature from 75° to 245° F (297 to 392 K) at choked-flow conditions.

The dependence of oscillator output frequency on molecular weight of the flowing gases and other variables was investigated. An intended application for this fluidic oscillator is to monitor the molecular weight of the inert gases considered for use in a Brayton-cycle space power system. Another possible application is to detect humidity in a hydrogen-steam mixture (ref. 5).

SYMBOLS

f	frequency of oscillation, Hz
g	acceleration due to gravity, 32.2 ft/sec^2 (980.7 cm/sec^2)
K_1	proportionality constant for eq. (1), $\sec\sqrt{\frac{(\text{lb mole})}{\text{lb}}}$ $\left(\sec\sqrt{\frac{(\text{g mole})}{\text{g}}}\right)$
K_2	proportionality constant for eq. (3), $\sec\sqrt{\frac{(\text{lb mole})}{\text{lb}}}$ $\left(\sec\sqrt{\frac{(\text{g mole})}{\text{g}}}\right)$
K_3	proportionality constant for eq. (5), $\sec\sqrt{\frac{(\text{lb mole})\ {}^{o}\text{R}}{(\text{lb})}}$ $\left(\sec\sqrt{\frac{(\text{g mole})\ \text{K}}{\text{g}}}\right)$
l	length of single feedback channel, in. (cm)
M	molecular weight
R	universal gas constant, 1545 ft-lb/(lb mole)(^{o}R) (8.3143 J/(kg mole)(K))
T	temperature, ^{o}F (K)
T_s	switching time, sec
γ	specific-heat ratio

APPARATUS AND TEST PROCEDURE

The oscillator tested is a fluidic bistable amplifier in which part of the output flow is fed back to the control ports (fig. 1). A basic principle of operation for this type of fluidic oscillator is that a pressure pulse will propagate through the feedback channel at sonic velocity. (Ref. 4 presents a detailed description of the principles of fluidic oscillators.) The length of the feedback channel (2 in. or 5 cm) was selected in order to obtain high frequency of oscillation and thus greater output sensitivity. Gas flowing through the oscillator is discharged through a vent hole in each feedback channel and then directed into a common output passage. The oscillator was designed, fabricated, and tested at the Lewis Research Center.

The apparatus used in conducting these tests is shown schematically in figure 2. The pressure drop across the oscillator was varied from approximately 6 to 30 psi

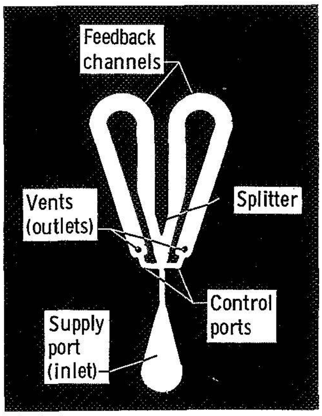


Figure 1. - Fluidic oscillator (full scale).

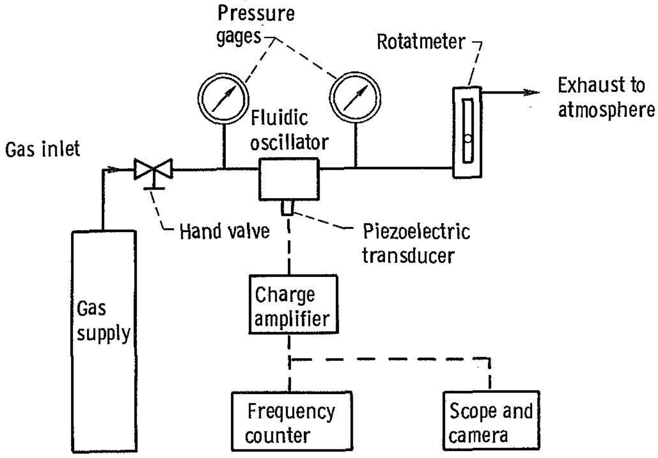


Figure 2. - Test apparatus.

(4 to 21 N/cm^2) by controlling a hand valve upstream of the fluidic oscillator. Gas pressures at the oscillator inlet and outlet were observed on calibrated pressure gages, but no internal pressure changes could be measured. Gas flow was obtained from a calibrated rotameter (0 to 92 standard ft^3/hr or 0 to 2.6 standard m^3/hr) before being exhausted to the atmosphere. The frequency of oscillation was sensed by a piezoelectric transducer inserted into one of the feedback loops to measure the pressure pulses. This transducer was connected to a charge amplifier in which the pressure pulse was converted to a frequency signal and read out on a counter to within an accuracy of 2 hertz. To determine the shape of the pressure pulse at various test conditions, an oscilloscope was connected to the charge amplifier and the trace recorded with a camera.

Testing of the oscillator was conducted in two phases. Phase 1 consisted of varying the pressure drop of the gas across the oscillator at constant temperature. Nine gases

TABLE I. - PROPERTIES OF GASES USED IN OSCILLATOR TESTS

Gas	Molecular weight	Specific-heat ratio	Frequency,[a] Hz	Impurity content	
				Gas	Weight percent
Helium	4.00	1.66	7987	Total	0.075
Neon	20.18	1.64	3567		.006
Argon	39.94	1.668	2546		.090
Krypton	83.80	1.68	1762		.051
Nitrogen	28.02	1.404	2852		.065
Air (dry)	29.0	1.40	2804		-----
Carbon dioxide	44.01	1.30	2201		<1.0
Propane	44.10	1.13	2061	Butane and pentane combined	2.10
				Carbon dioxide	.12
Methane	17.27	1.31	3546	Ethane	3.57
				Carbon dioxide	.93
				Nitrogen	.79
				Propane	.34
				Butane	.20
				Helium	.04

[a]Oscillator output frequency obtained under choked-flow conditions and room temperature.

were used as working fluids: four monatomic gases (helium, neon, argon, and krypton) and five polyatomic gases (nitrogen, dry air, carbon dioxide, propane, and methane). The molecular weight and specific heat ratio of these gases, as given in reference 6, are presented in table I. An analysis to determine the purity of each gas was performed, and the results are also included in table I. Note that the molecular weight for methane was determined from the percentage of each constituent and the molecular weights given in reference 6.

Phase 2 consisted of varying the temperature of the gas as the pressure drop across the oscillator was maintained constant. The test apparatus was modified by inserting a heater upstream of the oscillator, installing a thermocouple at the oscillator inlet, and insulating the system. The temperature was varied from 75° to 245° F (297 to 392 K) and was detected to the nearest 1° F on a calibrated pyrometer. Pressure in the heater was maintained at approximately 45 psia (30 N/cm^2). Three gases were used in phase 2: one monatomic gas (argon) and two polyatomic gases (nitrogen and carbon dioxide).

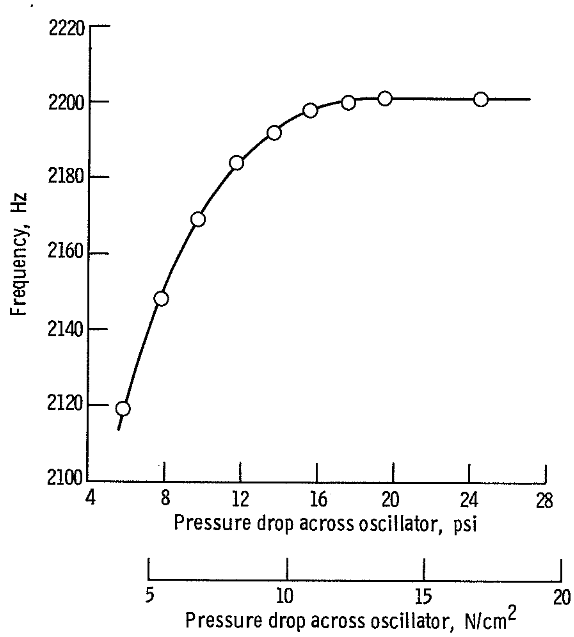


Figure 3. - Typical curve of frequency variation with pressure drop. Gas, carbon dioxide; temperature, 71° F (295 K); exhaust pressure, atmospheric.

DISCUSSION OF RESULTS

Pressure Drop

Testing in phase 1 was performed at ambient temperature over a range of pressure drops across the fluidic oscillator. Figure 3 shows the relation between pressure drop and oscillator frequency for carbon dioxide. This curve is typical for all the gases used and illustrates that output frequency varies with pressure drop until choked flow is reached. Choking in the oscillator occurs at the minimum cross-sectional flow area, which in this case is the vent port (fig. 1).

Under choked-flow conditions, frequency becomes pressure independent. Pressure drops in the lines and in the fluidic oscillator caused the minimum ratio of the measured inlet to outlet pressure for choked flow to be greater than the theoretical critical pressure ratio, $\left(\frac{\gamma + 1}{2}\right)^{\gamma/(\gamma-1)}$. Using the perfect gas relations (ref. 7) for local to critical area ratio, the fluid within the feedback channel of the oscillator was found to have an average Mach number of approximately 0.1 for all the gases.

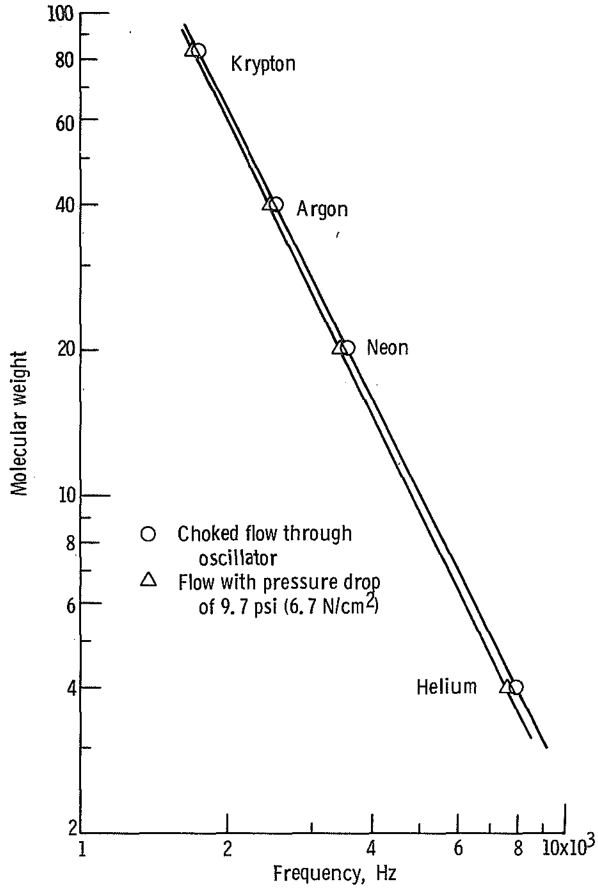


Figure 4. - Variation of molecular weight with frequency for monatomic gases. Gas temperature, 71° F (295 K).

Molecular Weight

Application for this fluidic oscillator is to measure the molecular weight of the inert gases considered for use in a Brayton-cycle space power system. Emphasis was therefore placed on obtaining a correlation between the oscillator frequency and molecular weight for monatomic gases. The variable used to obtain this correlation was sonic velocity. Figure 4 shows that at constant temperature and at constant pressure or choked flow, $1/f^2$ varies directly with M. Two curves are presented in figure 4; one curve was obtained at a constant pressure drop of 9.7 psi (6.7 N/cm^2), while the other was obtained at choked-flow conditions, approximately 30 psi (21 N/cm^2). The frequency variation from a pressure drop of 9.7 psi (6.7 N/cm^2) to choked conditions ranged from 40 hertz for krypton to 356 hertz for helium.

The polyatomic gases used have specific-heat ratios varying from 1.13 to 1.40 as shown in table I. A linear relation was found when $1/f$ was plotted against $\sqrt{M/\gamma}$

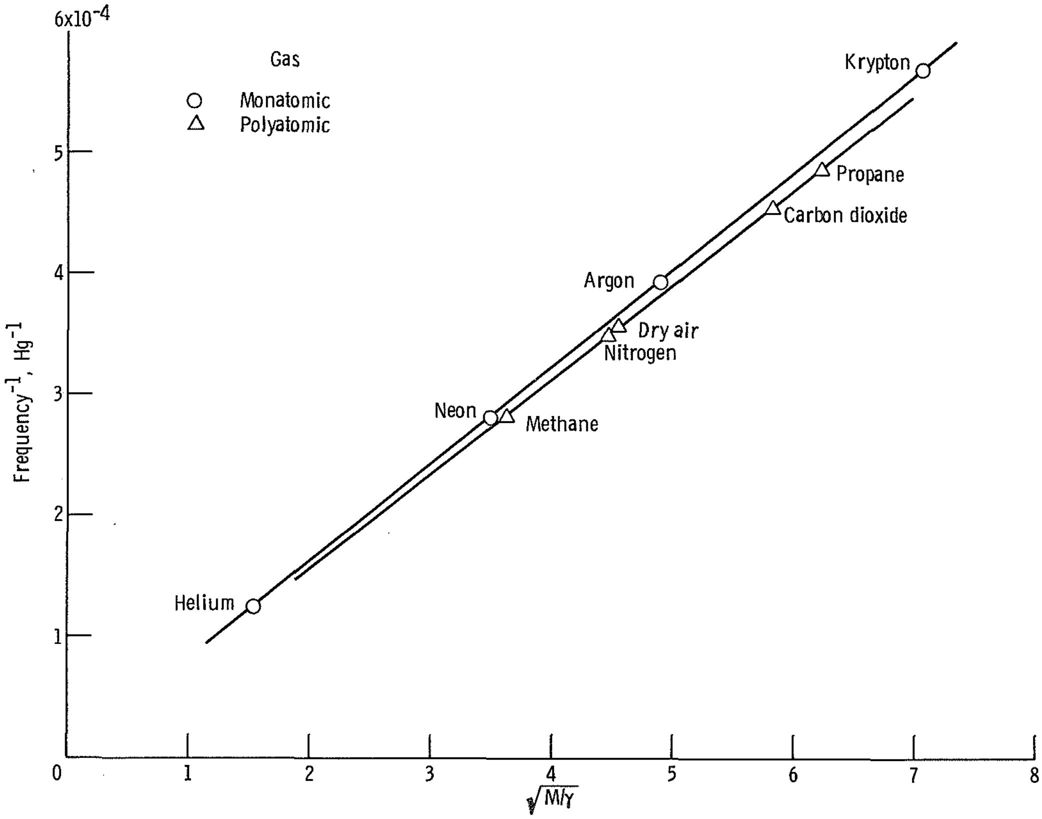
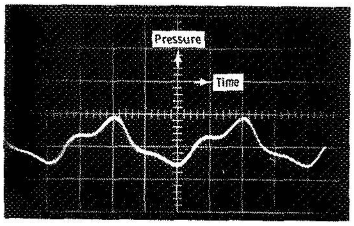


Figure 5. - Effect of various gases on oscillator output frequency. Gas temperature, 71° F (295 K); choked flow through oscillator.

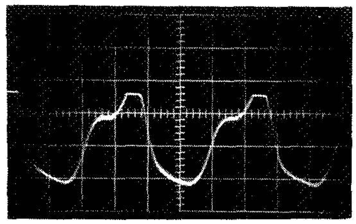
(fig. 5), which shows that frequency is proportional to sonic velocity at constant temperature and choked flow conditions. Also plotted in figure 5 are the data for the monatomic gases. The two distinct curves obtained show that the constants of proportionality for polyatomic gases and monatomic gases are different.

Photographs were taken of the oscilloscope traces during the phase 1 testing. Figure 6 shows typical traces for air and argon under choked and unchoked flow conditions. Amplitude of the pressure pulse is displayed on the y-axis, and the period is displayed on the x-axis. As conditions through the oscillator change from unchoked to choked flow, the overall shape of the waveform changes from an approximately sinusoidal shape to almost a square wave.

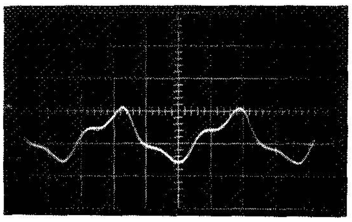
Although stable frequency readings on the counter were not obtained until a pressure differential of 6 psi (4 N/cm^2) was reached, repeatable and noise-free traces were seen on the oscilloscope with differential pressures as low as 2 psi (1.4 N/cm^2). Oscilloscope observation showed that a certain minimum pressure drop is needed between 1 to 2 psi (0.7 and 1.4 N/cm^2) for this oscillator to produce switching.



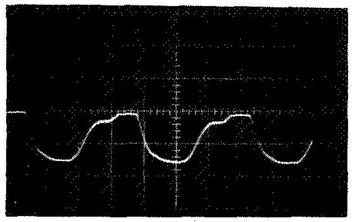
(a) Argon gas; pressure drop, 9.7 psi (6.7 N/cm^2); frequency, 2479 hertz.



(b) Argon gas; pressure drop, 24.3 psi (16.8 N/cm^2); frequency, 2543 hertz.



(c) Dry air; pressure drop, 8.0 psi (5.5 N/cm^2); frequency, 2713 hertz.



(d) Dry air; pressure drop, 30.0 psi (20.7 N/cm^2); frequency, 2804 hertz.

Figure 6. - Typical oscilloscope traces of pressure pulse.

Transport Time and Switching Time

Since the curves of figure 5 would go through the origin if extended, the general relation for the oscillator with constant gas temperature is

$$\frac{1}{f} = K_1 \sqrt{\frac{M}{\gamma}} \tag{1}$$

where K_1 is a constant equal to the slope of the curve. However, for a pressure pulse traveling through a bistable fluidic oscillator 1/2 the total period equals transport time plus switching time, or

$$\frac{1}{2f} = \frac{l}{\sqrt{\frac{\gamma g R T}{M}}} + T_s \tag{2}$$

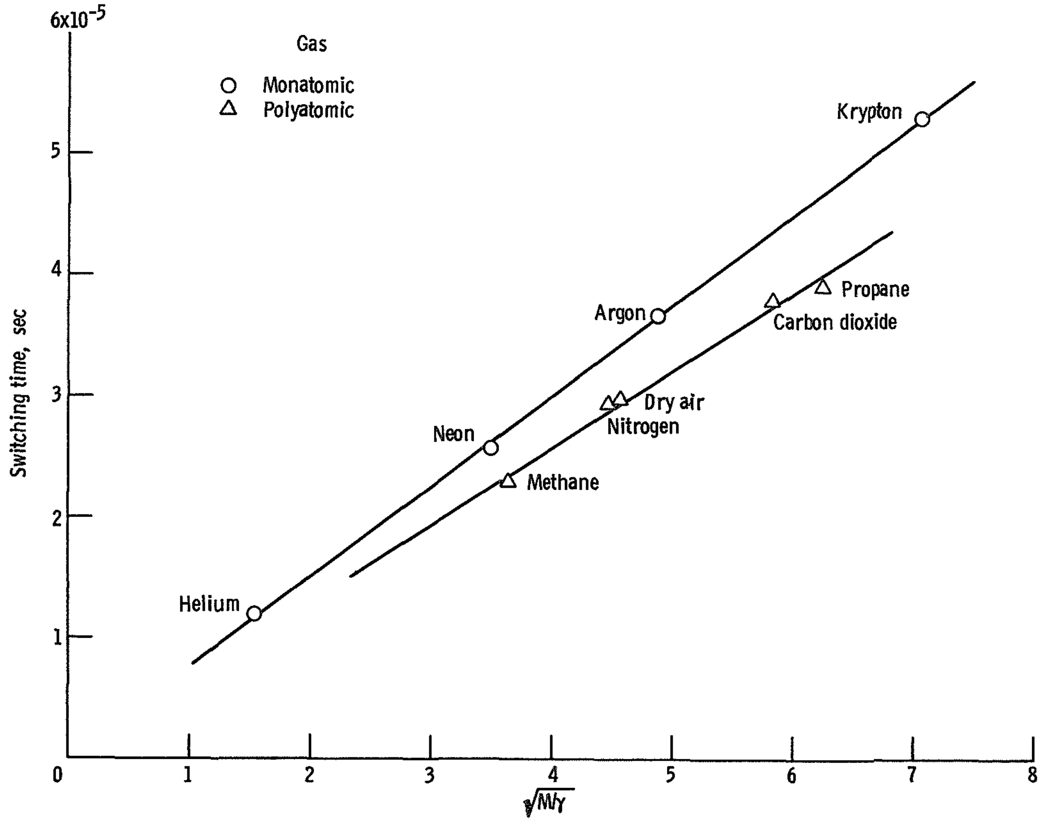


Figure 7. - Calculated switching time for monatomic and polyatomic gases. Gas temperature, 71° F (295 K); choked flow through oscillator.

Transport time is the time required for the pressure pulse to traverse one leg of the oscillator, and switching time is the elapsed time between initiation of the control pulse and flow in the alternate oscillator leg. Switching time can be calculated using the data found in table I and equation (2). These data are plotted in figure 7, and the result is a linear relation between T_s and $\sqrt{M/\gamma}$. Therefore, switching time was also found to be inversely proportional to sonic velocity. For a specific value of $\sqrt{M/\gamma}$ it was calculated that the switching time for monatomic gases was approximately 14.5 percent higher than that for polyatomic gases. With the experimental uncertainties involved, these curves also may be drawn through the origin to give the relation

$$T_s = K_2\sqrt{\frac{M}{\gamma}} \tag{3}$$

where K_2 is a constant equal to the slope of the curve and dependent on oscillator geometry. The effects of oscillator geometry on switching time are discussed in reference 8.

When equations (2) and (3) are combined, the general relation for the oscillator at constant temperature can be expressed as

$$\frac{1}{f} = 2\left(K_2 + \frac{l}{\sqrt{gRT}}\right)\sqrt{\frac{M}{\gamma}} \tag{4}$$

Temperature

Phase 2 consisted of testing the oscillator with three gases (argon, nitrogen, and carbon dioxide) at temperatures ranging from 75° to 245° F (297 to 392 K) at choked flow conditions. As expected from the proportionality of frequency and sonic velocity, a linear relation is seen in figure 8 between f and $\sqrt{T}$ for each of the three gases. It is

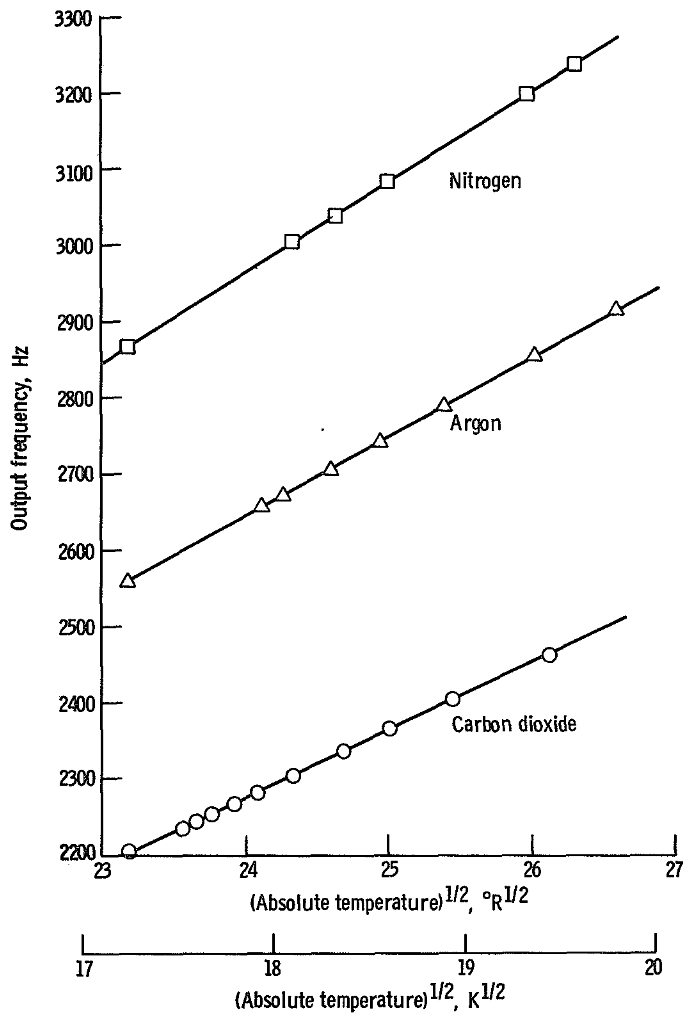


Figure 8. - Temperature effect on oscillator output frequency. Choked flow through oscillator.

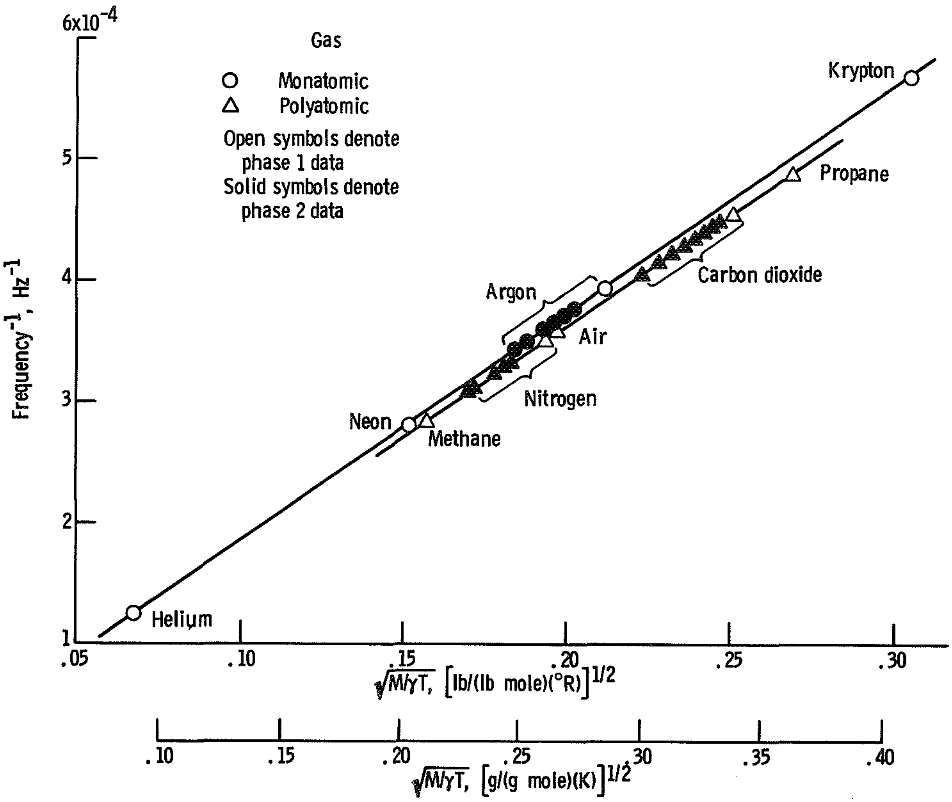


Figure 9. - Effect of temperature on oscillator performance using various gases. Choked flow through oscillator.

this linear relation that allows a fluidic oscillator to be used as a temperature sensor (ref. 4).

Data from testing in phases 1 and 2 were plotted in figure 9 to obtain curves of $1/f$ against $\sqrt{M/\gamma T}$. Once again, two distinct straight lines were obtained, one for the monatomic gases and another for the polyatomic gases. Both curves would pass through the origin and substantiate the relations found in phase 1 from figure 5 at ambient temperature. The differing characteristics with monatomic and also polyatomic gases only partially result from the greater variation in γ with pressure for the polyatomic gases (ref. 9). The final relation becomes

$$\frac{1}{f} = K_3 \sqrt{\frac{M}{\gamma T}} \tag{5}$$

where K_3 is dependent on oscillator geometry such as path length and splitter shape.

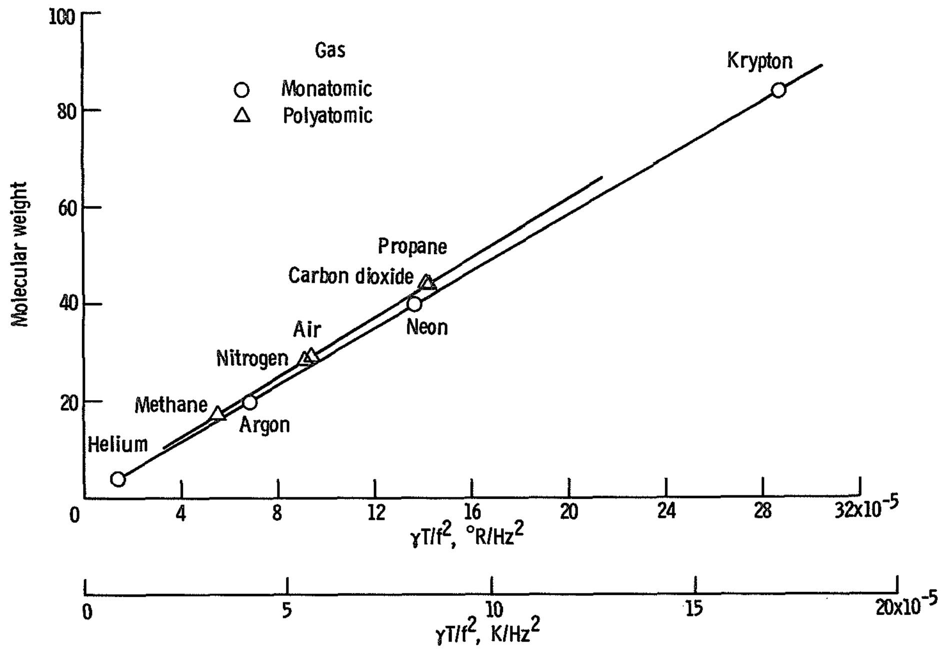


Figure 10. - Summary of oscillator performance. Choked flow through oscillator.

Combination Effects

In application of this oscillator to measure molecular weight, not only must oscillation frequency be determined but also the additional effects of temperature and gas properties must be included. For choked-flow conditions, the relation between molecular weight and $\gamma T/f^2$ is shown by figure 10 for all gases tested. For any one of these gases, the value of $\gamma T/f^2$ remains constant within 1 percent for changes in temperature from 75° to 245° F (297 to 392 K).

SUMMARY OF RESULTS

A fluidic oscillator was investigated for use as a molecular-weight sensor. Above a minimum pressure drop across the oscillator required in order to produce switching, the following results were obtained:

1. Oscillator output frequency was stable and proportional to sonic velocity at choked-flow conditions. But the constant of proportionality was different for monatomic and polyatomic gases.

2. For each gas, frequency varied with the pressure drop across the oscillator until choked-flow was reached. For choked conditions, the frequency was pressure independent.

3. For either choked-flow or constant pressure drop, switching time was inversely proportional to sonic velocity.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 23, 1969,
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