NRL REPORT 3741

FR-3741

UNCLASSIFIED

SEVENTH PARTIAL REPORT ON THE PULSE-JET ENGINE

MEASUREMENT OF THE AIR-FUEL RATIO

D. W. Baker

October 6, 1950

Approved by:

Mr. L. F. Campbell, Head, Thermodynamics Branch
Dr. G. R. Irwin, Superintendent, Mechanics Division

DEPARTMENT OF THE NAVY OFFICE OF NAVAL RESEARCH

NAVAL RESEARCH LABORATORY
CAPTAIN F. R. FURTH, USN, DIRECTOR
WASHINGTON, D.C.

DISTRIBUTION

BuAer	5
CNO	1
CO & Dir., USNEL	2
Wright-Patterson AFB	
Attn: BAU-CADO	1
Attn: CADO-E1	2
OCSigO	
Attn: Ch. Eng. & Tech. Div., SIGTM-S	1
CG, SCEL	
Attn: SCEL Liaison Office	3
Div. of Public Documents, GPO	
Attn: Library	1
Office of Tech. Services, Dept. of Commerce	2
RDB	
Attn: Information Requirements Branch	2
Attn: Navy Secretary	1
ANAF/GM Mailing List No. 13, Parts A, C, and DP	

UNCLASSIFIED

CONTENTS

ABSTRACT

For internal-combustion engines where steady flow exists in the exhaust system, the air-fuel ratio may be determined by calculations based in the chemical analysis of the products of combustion. However, the exhaust process in the pulse-jet engine is an intermittent and pulsating one; consequently, the question arises whether or not the air-fuel ratio can be determined by the above method. This report presents data which show that the air-fuel ratio for the pulse-jet engine may be determined by the chemical analysis for the amount of carbon dioxide, free oxygen, and carbon monoxide in the exhaust gases, provided that engine operation is steady and that the samples are drawn from a position between the forward part of the tailpipe inflow and the initial combustion zone.

PROBLEM STATUS

This is a final report on one phase of the problem; work on other phases continues.

AUTHORIZATION

NRL Problem P04-01R
NR 484-010

SEVENTH PARTIAL REPORT ON THE PULSE-JET ENGINE
MEASUREMENT OF THE AIR-FUEL RATIO

INTRODUCTION

The purpose of this investigation was to find whether a usable correlation could be obtained between exhaust-gas composition and measured air-fuel ratio, thereby eliminating the need for flow-measuring equipment, such as flowmeters, orifices, manometers, and ballast box.

The intermittent nature of the intake flow to a pulse-jet engine makes difficult the determination of the air-fuel ratio. Measurements from flowmeters and orifices are reliable only under steady conditions, and therefore it is necessary to smooth the flow by inserting a large ballast box into the air intake line. This box is the largest part of the equipment; even for an engine of moderate size—8 inches by 73 inches—a box of volume 125 ft^3 is required.

The air flow through the grid of a pulse-jet engine and the fuel flow were measured during a series of tests. Concurrently, exhaust-gas samples were collected and later analyzed for percent carbon dioxide, free oxygen, and carbon monoxide. The measured air-fuel ratios were correlated with calculated air-fuel ratios based on the gas analyses. Two sets of calculations were made; one based on the analyses only, and the other based on the analyses with assumed values for free hydrogen equal to 50 percent of the carbon monoxide formed and an assumed value for methane equal to 0.3 percent of the products.

EQUIPMENT AND PROCEDURE

The engine used in these tests was a "straight-tube" pulse-jet engine, 8 inches by 73 inches including tailpipe bell. The fuel system, located between the grid and the combustion chamber, consisted of four fan-spray jets. This system was of the continuous-flow type. The design of the engine was not changed during the series of tests; that is, the length, diameter, and fuel system remained essentially unchanged. However, in order to vary the operating characteristics of the engine, three different grids were used.

The test procedure consisted of starting the engine using spark ignition and a jet of compressed air through the grid; regulating the fuel rate for each run; taking simultaneous gas samples, air-flow measurements, and fuel-rate readings; and stopping the engine.

A water-cooled sampling tube shown in Figures 1 and 2 was used to draw the samples from the engine. The heat-transfer rate for the water-cooled sampling tube was approximately 20,000 BTU/hr or 280,000 BTU/ft^2hr. The tube handled 375 pounds of cooling water per hour, which was sufficient to keep it from melting. Attempts to draw gas samples through uncooled stainless-steel sampling tubes proved unsuccessful because the average temperature of the gas stream was above the melting point of the steel used.

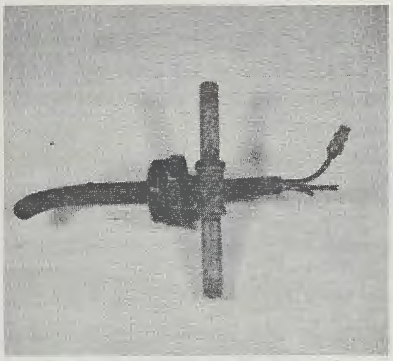

Figure 1 - Photograph of water-cooled sampling tube

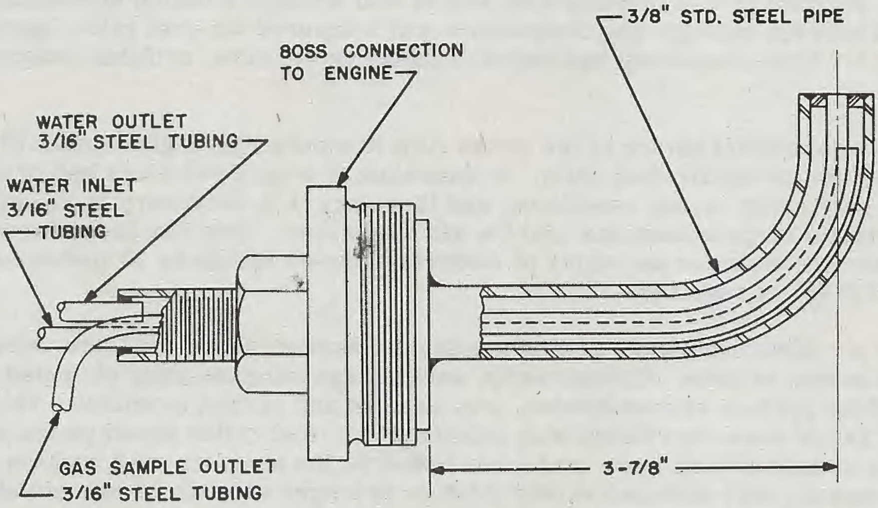

Figure 2 - Sketch of water-cooled sampling tube

In order to determine the optimum position for drawing gas samples forward of the tailpipe inflow, gas samples were taken from two positions along the axis of the engine, 23 inches and 39.5 inches from the exit of the tailpipe. The analysis of samples taken in the aft or 23-inch position did not show good reproducibility. Samples taken at the forward or 39.5-position were more reproducible, and, furthermore, the air-fuel ratio calculated from samples taken at this point agreed with the measured air-fuel ratio. Consequently, all subsequent samples were drawn from this position, which was assumed to be between the forward part of the tailpipe inflow and the initial combustion zone.

The gas samples were drawn from the engine by the water displacement method and were stored in gas sampling bottles under the average pressure in the engine. To investigate the possibility of leakage from the gas bottles, some bottles were stored under water from the time of drawing the sample until the time of analysis. No loss of carbon dioxide was noted between the two methods of storage; that is, under water and in the atmosphere.

The time elapsing between sampling and analysis varied from one hour to two days. No effect of storage time was noted on the analyses.

One hundred cc gas samples were analyzed with an Orsat gas analyser in the conventional manner. Potassium hydroxide, pyrogallol, and cuprous chloride solutions were used to absorb carbon dioxide, oxygen, and carbon monoxide respectively.

Air flow through the grid was determined by measuring the static pressure drop across a calibrated orifice mounted on an air box. A Hays draft gage, calibrated against a U-tube vertical manometer, was used to measure the pressure drop. Figure 3 shows the calibration curve for the Hays gage.

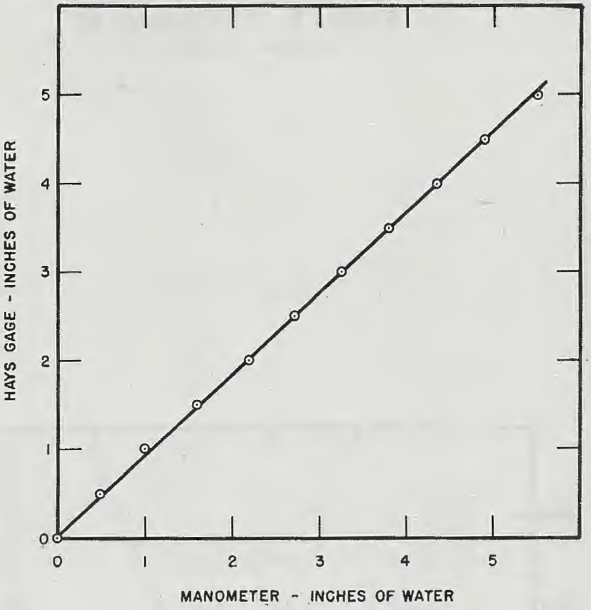

Figure 3 - Calibration of Hays draft gage versus U-tube vertical manometer

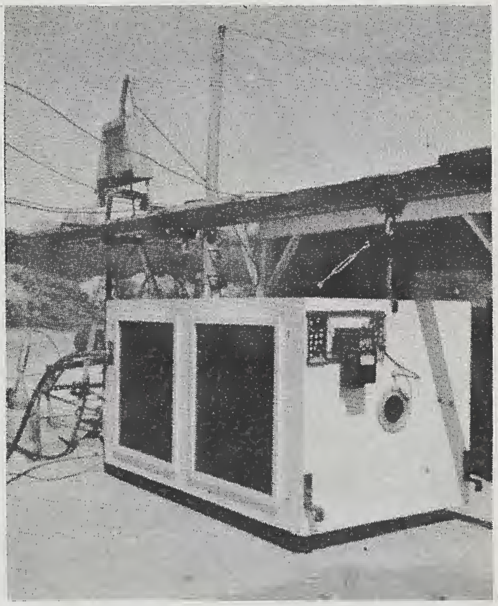

Figure 4 - 125-cubic-foot air box with Hays draft gage

In order to make the air flow through the orifice reasonably constant, two provisions were made: (1) the capacity of the ballast box was increased from 54 cubic feet to 125 cubic feet, and (2) a total of four holes, each three feet square, were cut in two sides and covered with flexible rubber 1/16 inch thick. This provision enabled the engine to "breathe" and kept the pressure inside the air box more constant. Figure 4 shows the air inlet end of the air box with the Hays gage mounted on the air box.

Air flow through the 6-inch orifice was computed from the following expression[1] and plotted on Figure 5 for various Δh_w and t:

$$M = 48{,}000 \sqrt{\frac{\Delta h_w}{459 + t}}$$

---

[1] Larsen, L. R., "Measurement of Air Flow by Means of an Orifice Drum," NRL Technical Memorandum for File, April 20, 1943. NRL Letter Report F42 (315:LRL) dated June 2, 1943

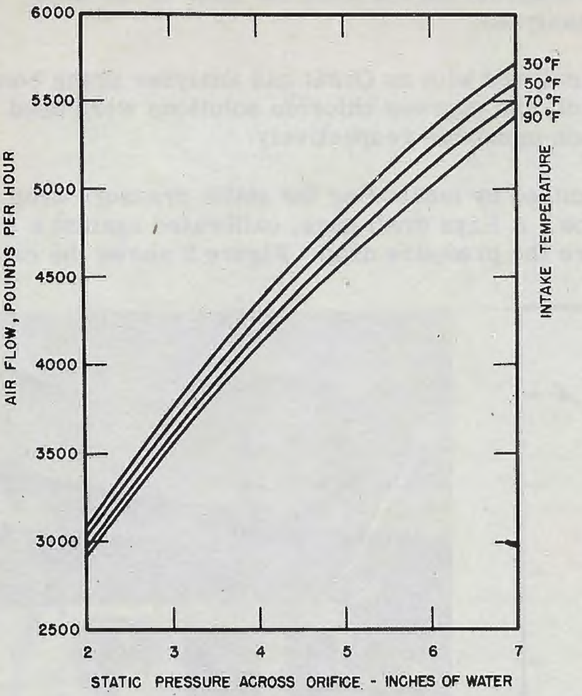

Figure 5 - Calibration of 6-inch orifice

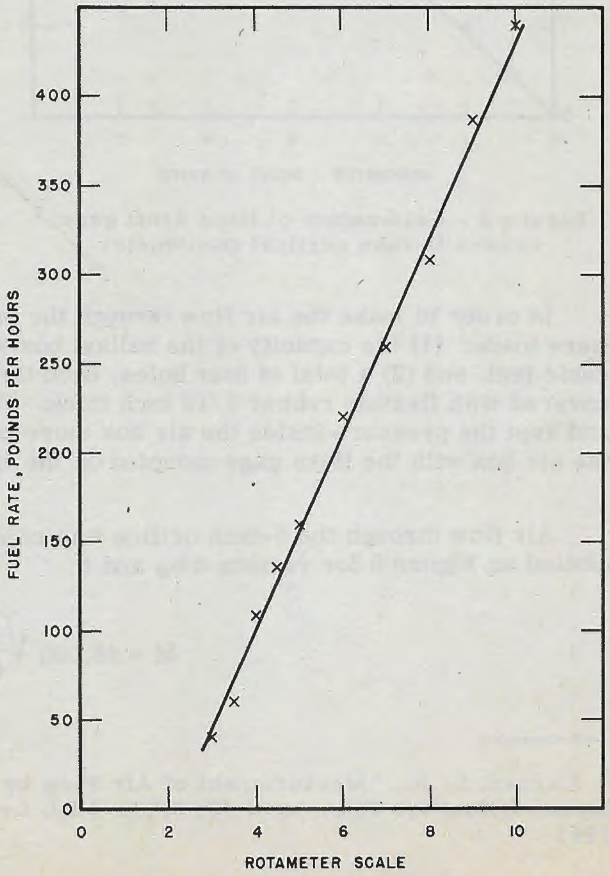

Figure 6 - Calibration of Fischer-Porter fuel rotameter No. H5-1451

where Δh_W = inches of H_2O

$t = {}^0F$

M = pounds per hour.

This expression is based on a barometric pressure of 30 inches of mercury, an orifice constant of 0.59, and an expansion or compressibility factor of 1.0.

Fuel flow was measured by a Fischer-Porter float-type rotameter previously calibrated with the same fuel used in the tests. The calibration curve for the rotameter is shown in Figure 6. The fuel used was a low-octane unleaded aviation gasoline.

RESULTS

Calculations of air-fuel ratio, fuel composition, and amount of water vapor formed during combustion were made by means of oxygen and nitrogen balances. The air composition was assumed to be 20.9 percent oxygen and 79.1 percent nitrogen by volume, that is $N_2/O_2 = 3.78$.

Data of previous investigators indicate appreciable amounts of hydrogen and unburned hydrocarbons, principally methane, in the exhaust products of internal combustion engines utilizing the same type of fuel as that used in these tests. Gerrish and Tesserman[2] found from research on one multicylinder and four single-cylinder engines that the hydrogen content of the exhaust products can be expressed by the equation: $H_2 = 0.51(CO)$. The methane content was found constant at 0.22 percent for all air-fuel ratios. D'Alleva and Lovell[3] reported methane contents from 0 to 0.7 percent with an average content of 0.3 percent from data obtained on three multicylinder automotive engines. The two above investigations reported fuels used with values of H/C in the range of 0.175 to 0.185 which corresponds to the average values determined from these tests.

Small amounts of aldehydes and oxides of nitrogen are also produced in the combustion, but their concentrations are too low to affect the calculation of the air-fuel ratio.

Analyses for hydrogen and methane were not made from the exhaust-gas samples drawn. However, calculations of air-fuel ratios with assumed values of hydrogen and methane were made and compared with the measured ratios. The hydrogen was assumed to be equal to one half the carbon monoxide formed and the methane was assumed constant at 0.3 percent of the products. Also, the calculated ratios based on the carbon dioxide, oxygen, and carbon monoxide only were made and compared with the measured values. Figures 7, 8, and 9 show these values of air-fuel ratio plotted against fuel rates. The following expressions[4] were used for the calculated ratios:

---

[2] Gerrish, H. C., and Tesserman, A. M., "Relation of Hydrogen and Methane to Carbon Monoxide in Exhaust Gases from Internal-Combustion Engines." NACA Report No. 476, p. 9., 1933

[3] D'Alleva, B. A., and Lovell, W. G., "Relation of Exhaust Gas Composition to Air-Fuel Ratio." S. A. E. Jour., Vol. 38, No. 3., pp. 90-98, March 1936

[4] See, for example, Faires, V. M., "Applied Thermodynamics," (Macmillan 1948), p. 206ff

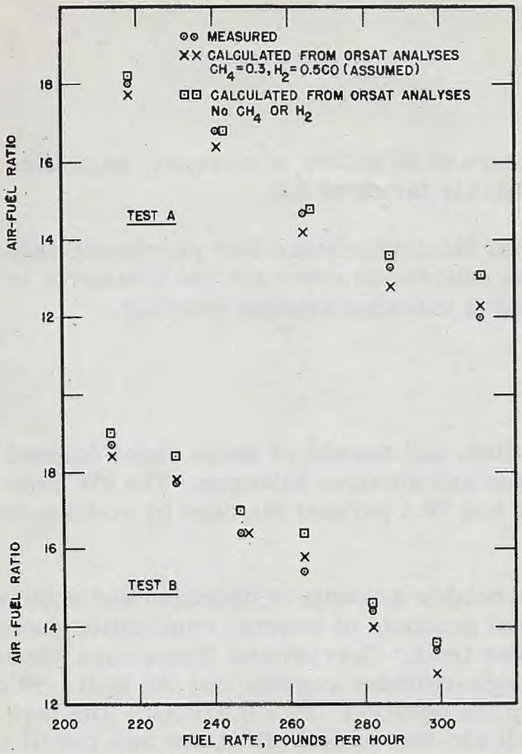

Figure 7 - Comparison of calculated and measured air-fuel ratios, Grid I

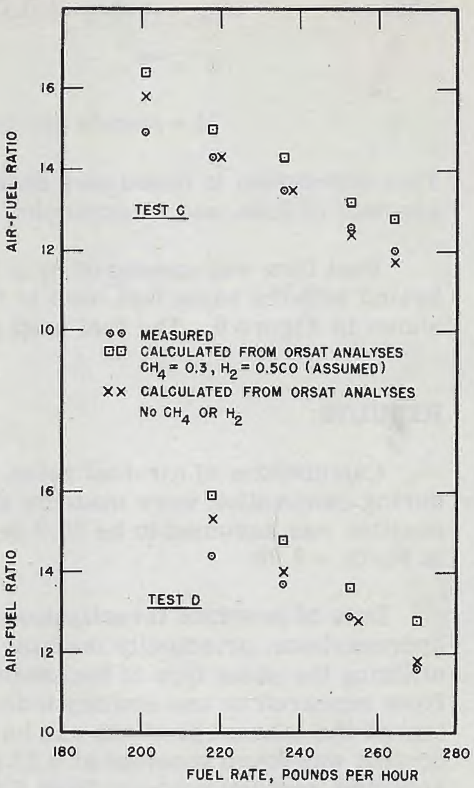

Figure 8 - Comparison of calculated and measured air-fuel ratios, Grid II

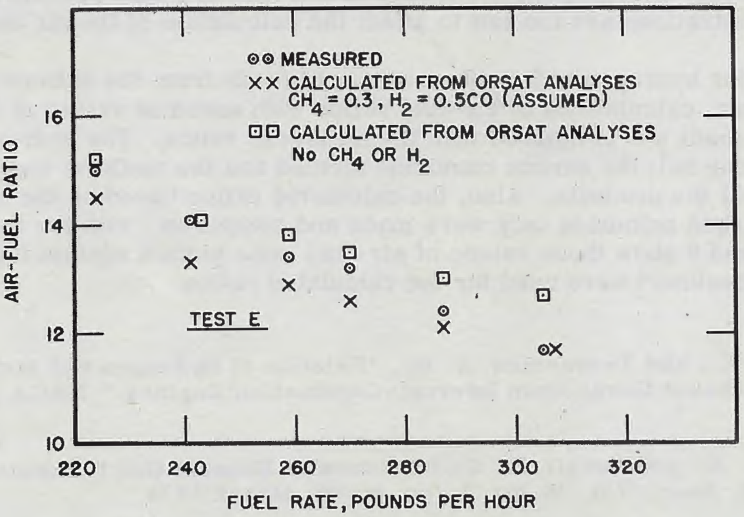

Figure 9 - Comparison of calculated and measured air-fuel ratios, Grid III

$$A/F = \frac{36.4N_2}{1.05N_2 + 8CO_2 - 4O_2 + 11CO + 4.8} \qquad (1)$$

where $N_2 = (100\text{-}CO_2\text{-}1.5CO\text{-}O_2\text{-}0.3)$ percent

CO_2, CO, O_2 = percent

CH_4 = 0.3 percent (assumed constant)

H_2 = 0.5 CO percent (assumed).

$$A/F = \frac{36.4N_2}{1.05N_2 + 8CO_2 - 4O_2 + 10CO} \qquad (2)$$

where $N_2 = (100\text{-}CO_2\text{-}CO\text{-}O_2)$ percent

CO_2, CO, O_2 = percent

$CH_4 = H_2 = 0.$

The maximum deviation of the calculated air-fuel ratio with assumed hydrogen and methane from the measured values was minus 5.7 percent on those runs during which the engine operation was steady (i.e. operated at constant frequency). The average deviation for the same runs and assumed hydrogen and methane was minus 1.2 percent. Correspondingly, the average and maximum deviation of the calculated air-fuel ratio with no assumed hydrogen and methane from the measured values were plus 4.2 percent and plus 10.3 percent respectively.

Observed and calculated data for all tests are tabulated in Table 1. These runs in which engine operation was unsteady (surging) are indicated. Results of calculations for water vapor formed and fuel composition are given for assumed hydrogen and methane.

The percent of carbon dioxide, oxygen, and carbon monoxide are plotted in Figure 10 against calculated air-fuel ratios, with assumed methane and hydrogen. The data plotted are a composite of all runs made and hence show the relationship between the exhaust-gas constituents and calculated air-fuel ratio for all grids tested. The solid lines in Figure 10 are based on combustion calculations for $C_8H_{17.6}$, an assumed fuel in which the m/n ratio* was taken as the average value from Table 1 for tests A, B, C, D, and E for assumed hydrogen and methane. The following equation was used in these calculations.

$$C_8H_{17.6} + eO_2 + 3.78\,e\,N_2 = aCO_2 + bH_2O + 0.3CH_4 + (8\text{-}a\text{-}0.3)CO + dO_2 + (8\text{-}a\text{-}03)H_2/2 + 3.87\,eN_2.$$

where e = moles O_2 supplied (assumed)

a = moles CO_2 in products

b = moles H_2O in products

d = moles free O_2 in products

---

* Atoms of hydrogen per atom of carbon in the fuel.

TABLE 1
Calculated Results of Air Box and Orsat Analyses

			Air-Fuel Ratio					Exhaust Gas Analysis Volume Percent				
Test	Fuel Rate lb/hr	Air Flow lb/hr	Measured Air Box	Computed $CH_4 = 0.3$ $H_2 = 0.5CO$	% Deviation from Measured	Computed No CH_4 or H_2	% Deviation from Measured	CO_2	O_2	CO	H_2O** mols/100 mols dry gas	Computed Fuel Composition*** m/n
Grid I												
A-2	218	3940	18.0	17.7	-1.7	18.2	1.1	11.8	4.2	0.2	12.0	2.06
-4	241	4060	16.8	16.4	-2.4	16.8	0	12.7	2.6	0.3	13.4	2.13
-6	264	3880	14.7	14.2	-3.4	14.8	0.7	13.1	0.9	1.8	14.2	2.06
-8	287	3820	13.3	12.8	-3.8	13.6	2.3	12.7	0.2	3.6	13.8	1.95
-10	311	3720	12.0	12.3	+2.5	13.1	9.2	11.0	0	5.6	15.0	2.18
B-1	213	3990	18.7	18.4	-1.6	19.0	1.6	11.3	4.6	0.1	12.3	2.21
-2	230	4070	17.7	17.8	+0.6	18.4	4.0	11.6	4.1	0.2	12.7	2.22
-3	247	4050	16.4	16.4	0	17.0	3.7	12.1	2.9	0.7	13.5	2.21
-4	264	4060	15.4	15.8	+2.6	16.4	6.5	12.2	2.2	1.0	14.6	2.27
-5	282	4060	14.4	14.0	-2.7	14.6	1.4	12.4	0.5	2.5	15.6	2.32
-6*	299	4020	13.4	12.8	-4.5	13.6	1.5	11.6	0.5	4.5	14.2	2.05
Grid II												
C-1*	201	3000	14.9	15.8	+6.0	16.4	10.0	11.7	2.3	1.4	14.8	2.40
-2	218	3120	14.3	14.3	0	15.0	4.9	12.0	1.5	2.6	16.0	2.13
-3	236	3180	13.5	13.5	0	14.3	5.9	11.6	0.6	3.6	15.4	2.29
-4	253	3180	12.6	12.4	+1.6	13.2	4.8	11.8	0.3	4.8	13.6	1.97
-5	264	3180	12.0	11.7	-2.5	12.8	6.7	9.4	0.1	7.5	13.2	2.28
D-1*	218	3150	14.4	15.3	+6.3	15.9	10.4	12.5	1.6	1.1	15.0	2.32
-2	236	3230	13.7	14.0	+2.2	14.8	8.0	11.9	0.6	2.7	15.8	2.43
-3	253	3280	12.9	12.8	-0.8	13.6	5.4	11.0	0	4.9	16.0	2.35
-4	270	3150	11.6	11.8	+1.7	12.8	10.3	9.8	0	7.1	15.1	2.24
Grid III												
E-1	224	3370	15.0	14.5	-3.3	15.2	1.3	12.0	1.2	2.3	15.2	2.32
-2	241	3400	14.1	13.3	-5.7	14.1	0.0	11.2	0.4	4.1	15.5	2.40
-3	259	3480	13.4	12.9	-3.7	13.8	3.0	10.5	0.2	5.1	16.5	2.47
-4	270	3560	13.2	12.6	-4.6	13.5	2.3	10.4	0.2	5.6	15.9	2.37
-5	287	3560	12.4	12.1	-2.4	13.0	4.8	9.7	0.1	6.8	15.8	2.36
-6	305	3560	11.7	11.7	0	12.7	8.6	9.6	0.1	7.4	15.0	2.23

* Surging or irregular operation

** Based on assumed H_2 and CH_4

*** m/n is the ratio of number of hydrogen atoms per combination, based on assumed H_2 and CH_4

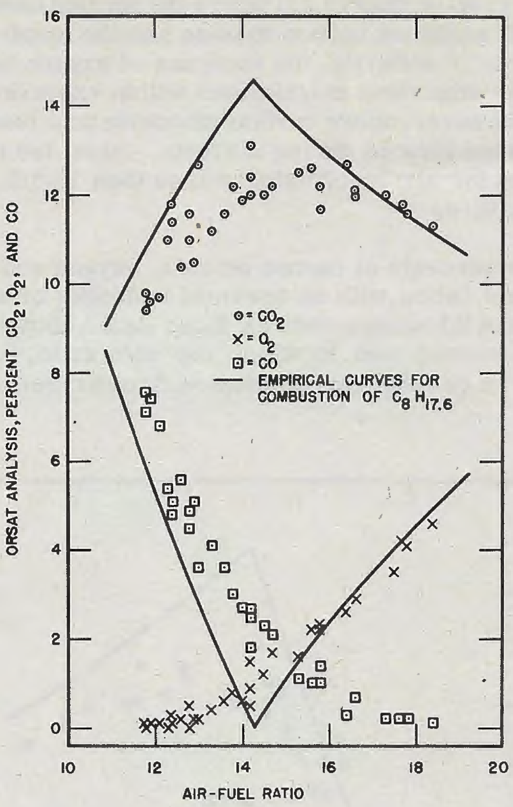

Figure 10 - Calculated air-fuel ratio, CH_4 = 0.3, H_2 = 0.5CO (assumed)

Assumptions were made as follows:

(1) The percent CO and H_2 were assumed zero for the stoichiometric ratio and for leaner mixtures, i.e., 8-a-0.3 = 0, hence a = 7.7.

(2) The percent free O_2 was assumed zero for the stoichiometric ratio and for richer mixtures.

(3) The percent H_2 was assumed equal to one-half of the CO formed for all mixtures richer than the stoichiometric.

(4) CH_4 was assumed 0.3 percent for all air-fuel mixtures.

(5) Unburned carbon was assumed zero.

From Equation (1) it is seen that the hydrogen balance is given by:

$$17.6 = 2b + 1.2 + 8-a-0.3$$
$$\text{or } 2b-a = 8.70;$$

and the oxygen balance is given by:

$$2e = 2a + b + 8-a-0.3 +2d$$
$$\text{or } 2e-2d-a-b- = 7.70.$$

For air-fuel ratios greater than 17.1:1 where the percent carbon monoxide formed was 0.1 to 0.2, the amounts of analyzed carbon dioxide and the empirical calculations agree within experimental error. Similarily, the analyses of oxygen for air-fuel ratios greater than 15.5:1 agree with the empirical calculations within experimental error. For air-fuel ratios less than 17.1:1, however, more carbon monoxide and less carbon dioxide than empirically calculated were formed during all tests. Also, the percent oxygen analyzed was more than calculated for air-fuel mixtures less than 15.5:1. These facts indicate poor combustion at richer mixtures.

Figure 11 shows the percents of carbon dioxide, oxygen and carbon monoxide plotted against calculated air-fuel ratios with no assumed hydrogen or methane. The solid lines are based on assumptions of the same nature as those listed above and on combustion calculations for $C_8H_{16.8}$, an assumed fuel in which the m/n ratio, 2.10, is the average value from calculations based on percent carbon dioxide, free oxygen, and carbon monoxide only.

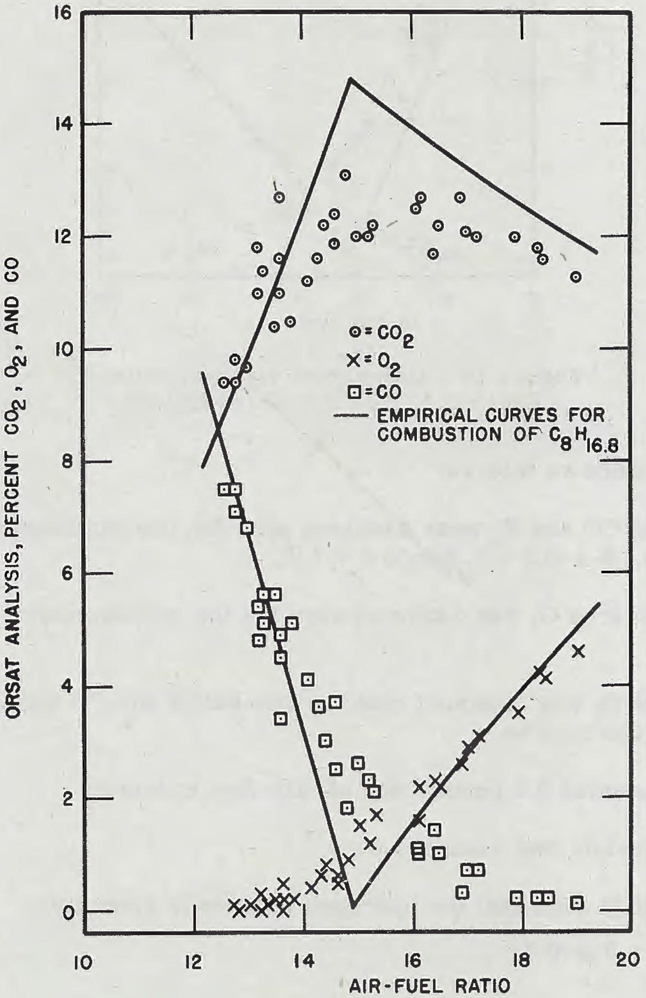

Figure 11 - Calculated air-fuel ratio, no CH_4 or H_2 assumed

Fuel composition was computed for each gas analysis as outlined below. The average H/C ratio, lbs hydrogen/lb carbon, calculated with hydrogen and methane assumed was 0.185 for all tests. These computations assume no unburned carbon. The average value of $m/n = 12H/C$, atoms of hydrogen per carbon atom, was 2.22. For computations where no hydrogen and methane was assumed, the corresponding average values were $H/C = 0.175$, and $m/n = 2.10$. For percent $H_2 = 0.5$ CO formed and percent $CH_4 = 0.3$:

$$H/C = \frac{W + CO/2 + 0.6}{6(CO_2 + CO + 0.3)} \text{ lb hydrogen/lb carbon.}$$

For percent $H_2 = CH_4 = 0$:

$$H/C = \frac{W}{6(CO_2 + CO)} \text{ lb hydrogen/lb of carbon,}$$

where W is the amount of water vapor formed in moles.

ACCURACY OF RESULTS

The maximum expected difference between calculated and measured air-fuel ratios was found to be 7.6 percent, based upon the accuracy of each measurement and each instrument used. This deviation was divided as follows: 1.7 percent for the air-flow measurements, 2.4 percent for the fuel-flow measurements, and 3.5 percent for the calculated air-fuel ratios based on the gas analyses.

The Hays draft gage was capable of being read to 0.05 inches of water and the ambient air temperature was determined to an accuracy of ± 2°F. This gives a deviation in air-flow of 1 to 1.7 percent at pressure drops across the orifice on the air box of 2.00 to 4.00 inches of water at a 40°F air temperature. Fuel flow was measured by means of a Fischer-Porter rotameter, the tube of which was 250 millimeters long and graduated in millimeters. According to the manufacturer, this size tube so graduated can be read to ± 0.9 millimeter, or to a fuel rate accuracy of ± 4.7 pounds per hour for the fuel used. At a fuel rate of 200 pounds per hour the deviation would be 2.4 percent and would decrease to 1.4 percent at 330 pounds per hour.

The average of 2.6 percent deviation for the calculated air-fuel ratio is based on analyses of 100 cubic centimeter samples analyzed with apparatus having a burette capable of being read to 0.1 cubic centimeter. This figure represents the least count error of the instrument itself, and does not include possible errors due to leakage, oversaturation of the cuprous chloride solution resulting in inaccurate carbon monoxide readings, or absorption of carbon dioxide in the water used in the leveling bottle of the gas analyzer.

CONCLUSIONS

1. From the close correlation of measured and calculated values, it is concluded that the air-fuel ratio of the pulse-jet engine may be determined from the exhaust-gas analysis alone, provided the engine operation is steady and the sample is drawn from a position between the tailpipe inflow and the initial combustion zone. This eliminated the use of equipment to measure the air and fuel flow.

2. The pulse-jet engine investigated was found to operate within a range of air-fuel ratios from 11:1 to 19:1. This range corresponds to other types of internal-combustion engines burning gasoline.

3. The presence of some free hydrogen and unburned hydrocarbons, probably methane, is indicated from the comparison of the results with and without assumed hydrogen and methane.

ACKNOWLEDGMENTS

A word of acknowledgment is due T. O. Meyer, G. C. Milak, and R. A. Howard for assistance in conducting the experimentation at the Chesapeake Bay Annex of NRL.

* * *

NAVY-DPPO PRNC. WASH., D.C.