NASA Technical Memorandum 85676

NASA-TM-85676 19830024856

A NEW TECHNIQUE FOR MEASURING GAS CONVERSION FACTORS FOR HYDROCARBON MASS FLOWMETERS

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AUGUST 1983

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ABSTRACT

A new technique for measuring calibration conversion factors for hydrocarbon mass flowmeters has been developed. It has been applied to a widely used type of commercial thermal mass flowmeter for hydrocarbon gases. The values of conversion factors for two common hydrocarbons measured using this technique are in good agreement with the empirical values cited by the manufacturer. Similar agreements can be expected for all other hydrocarbons. The technique is based on Nernst theorem for matching the partial pressure of oxygen in the combustion product gases with that in normal air. It is simple, quick and relatively safe--particularly for toxic/poisonous hydrocarbons.

INTRODUCTION

Most of the current mass flowmeters for gaseous media depend on the thermal properties of the test gases. They are normally calibrated for air and then used for other gases either by use of a theoretical conversion factor or an empirical factor provided by the manufacturer. Since the theoretical conversion factors for many gases of interest, such as H_2, N_2, O_2, CO, CO_2, Freon 12, and hydrocarbon (C_xH_y), do not agree with the experimental values, it is often necessary to determine their calibration conversion factors experimentally. This is particularly true for most of the hydrocarbons. Even though the process of calibrating mass flowmeters for hydrocarbons of interest is not complicated, their conversion factors are often not available, particularly when the gases involved are rare or toxic. Any scheme which permits _in situ_ or online measurements of conversion factors for all hydrocarbons would thus be of great interest to combustion chemists and others interested in synthetic fuel development.

In the following sections we discuss a new technique for calibrating mass flowmeters for hydrocarbon gases. This technique is suitable for all hydrocarbons compatible with the materials of construction of the flowmeters and associated gas transport components.

LIST OF SYMBOLS

ℓ	air flowrate
m	oxygen flowrate
n	hydrocarbon flowrate
O_2	oxygen molecule
C_xH_y	hydrocarbon molecule containing x atoms of carbon and y atoms of hydrogen

CH_4	methane
C_2H_2	acetylene
E	oxygen-sensor output
P_1	oxygen partial pressure in the reference gas
P_2	oxygen partial pressure in the test gas
C(P)	cell constant
X_i	mole fraction of gas i
F	gas conversion factor (The meter indication is multiplied by this factor to obtain true flowrate for the test gas.)
C_p	specific heat at constant pressure

THEORETICAL BASIS OF THE TECHNIQUE

A sensitive technique$^{(1)}$ for measuring oxygen partial pressures in hydrocarbon combustion products has recently been developed. During the development phase of this technique, it became obvious that the technique could also be adapted for direct measurement of conversion factors for all hydrocarbon gas flowmeters.

The O_2-partial pressure monitor was developed for monitoring O_2-concentration in the output channel of the following combustion process$^{(2)}$:

$$\underset{\text{Input Channel}}{\left[\ell(\text{Air}) + m(O_2) + n(C_xH_y)\right]} \longrightarrow \underset{\text{Output Channel}}{\left[\begin{array}{l}\ell(\text{Air}) + nx(CO_2) + \frac{ny}{2}(H_2O) + \\ \left(m - n\left(\frac{4x+y}{4}\right)\right)(O_2) + \text{Heat}\end{array}\right]} \tag{1}$$

The O-$_2$content of the output channel is compared with that of reference air, using an electrochemical O_2 sensor. The sensor output depends on the oxygen partial pressure on its two sides, according to the following relation$^{(3)}$:

$$E = A\,\ell n\left(\frac{P_1}{P_2}\right) + C(P) \tag{2}$$

where E = sensor output

P_1 = oxygen partial pressure in the reference gas

P_2 = oxygen partial pressure in the test gas

$C(P)$ = cell constant.

Equation (2) reduces to the following form when the test gas and the reference air are at the same temperature and pressure.

$$E = A \, \ell n \frac{X_1}{X_2} + C(P) \qquad (3)$$

where X_i = mole fraction of oxygen in the medium i.

Mole fraction of oxygen in the output channel of equation (1) is given by the following equation:

$$X_2(O_2) = \frac{0.2095\ell + \left[m - n\left(\frac{4x + y}{4}\right) \right]}{\ell + nx + \frac{n}{2} y + \left[m - n\left(\frac{4x + y}{4}\right) \right]} \qquad (4)$$

If the mole fraction of oxygen in the output channel is same as in the reference gas (air), we obtain:

$$0.2095 = \frac{0.2095\ell + \left[m - n\left(\frac{4x + y}{4}\right) \right]}{\ell + nx + \frac{n}{2} + \left[m - n\left(\frac{4x + y}{4}\right) \right]} \qquad (5)$$

For the special case of $C_xH_y \equiv CH_4$, equation (5) simplifies as follows:

$$0.2095 = \frac{0.2095\ell + (m - 2n)}{\ell + (m + n)} \qquad (6)$$

and

$$\frac{m}{n} = 2.795$$

Calculated values of $\frac{m}{n}$ for other hydrocarbons are listed in Table I.

It is apparent from equation (7) that $\frac{m}{n}$ is independent of the value of ℓ, though the latter does determine the sustenance of the hydrocarbon combustion flame. The optimum value of ℓ ranges from 2 m to 3 m.

The condition specified by equations (6) and (7) is signaled by the production of the same oxygen sensor output as is obtained with air as the test gas. The relation between oxygen and methane concentrations given by equation (7) can be used as the basis for methane flowrate calculation if the oxygen flowrate were known. Oxygen conversion factors are usually supplied by the flowmeter manufacturers because of widespread use of oxygen in chemistry/combustion laboratories. Comparable relations exist between flowrates for oxygen and other hydrocarbons.

EXPERIMENTAL PROCEDURE

Figure 1 shows a schematic diagram of the experimental system used for equalizing partial pressures of oxygen in the test gas and the reference air. Typically, the hydrocarbon under test would be burnt in oxygen-enriched air in a well-stirred combustor in order to ensure complete combustion. A fraction of the combustion products would be passed through the oxygen partial pressure monitor. For a particular dial setting of the hydrocarbon-flowmeter, the oxygen flowrate would be adjusted to make the oxygen partial pressure in the output channel same as in the reference air. This condition would be signaled by the production of the same cell output as is obtained when normal air is used as the test gas. The hydrocarbon flowmeter conversion factor (F) would then be given by the following relation.

$$F = \frac{O_2\text{-Flowrate}}{\left(\frac{m}{n}\right)_{\text{Hydrocarbon}} (\text{Hydrocarbon flowrate on dial})} \tag{8a}$$

$$= \frac{O_2\text{-Flowrate}}{2.795\ (CH_4 \text{ flowrate on dial})} \text{ (for methane gas)} \tag{8b}$$

$$= \frac{O_2\text{-Flowrate}}{3.295\ (C_2H_2 \text{ Flowrate on dial})} \text{ (for acetylene gas)} \tag{8c}$$

We shall apply this technique to one class of linear mass flowmeters widely used in chemical and aerospace laboratories. However, the procedure is applicable to all other mass flowmeters, regardless of their operating principles.

Typical results obtained with methane and acetylene gases are summarized in Tables II and III and illustrated in figures 2 and 3. The agreement between the present experimental values and the empirical values listed by the flowmeter manufacturer(4) is quite good. It is also apparent that the CH_4 and C_2H_2 conversion factors are independent of the oxygen flowrates as well as the carrier medium (air) flowrates.

The last columns in Tables II and III list the values of conversion factors expected if the test gases were at STP during their transport through the heated element of the flowmeter.(4) However, the temperature and pressure of the test gases through the heated element are not standard and their values are not easily determinable. This makes their calculated conversion factor values suspect, thereby necessitating their experimental determination for all hydrocarbons and other gases whose C_p varies significantly with temperature and pressure.

CONCLUDING REMARKS

A new technique for measuring conversion factors for hydrocarbon flowrates with commercially available thermal mass flowmeters has been developed. This technique is simpler and safer, particularly for toxic/poisonous hydrocarbons. It is particularly suitable for combustion kinetics studies involving more complex hydrocarbons.

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   (b) Instruction Manual for Hastings Thermal Mass Flowmeters. Teledyne Hastings-Raydist Co., 1979.

TABLE I.- SUMMARY OF CALCULATED VALUES OF $\frac{m}{n}$ FOR SELECTED SATURATED UNBRANCHED ACYCLIC HYDROCARBONS.

Hydrocarbon	Chemical Formula (C_xH_y)	$\frac{m}{n}$
Methane	CH_4	2.795
Ethane	C_2H_6	4.825
Propane	C_3H_8	6.855
Butane	C_4H_{10}	8.885
Pentane	C_5H_{12}	10.915
Hexane	C_6H_{14}	12.945
Heptane	C_7H_{16}	14.975
Octane	C_8H_{18}	17.005
Nonane	C_9H_{20}	19.035
Decane	$C_{10}H_{22}$	21.065

TABLE II.- SUMMARY OF RESULTS FOR METHANE FLOWMETER CONVERSION FACTOR

Air-Flowrate (ℓ) cm^3/min (True Reading)	O_2-Flowrate (m) cm^3/min (True Reading)	CH_4-Flowrate (n) cm^3/min (Dial Reading)	Sample Gas Flowrate cm^3/min (Air Equivalent)	O_2-Partial Pressure Monitor Output (mV)	CH_4-Conversion Factor (F)	Theoretical Value$^{(4)}$ $\left(\frac{C_p(\text{Air}) \text{ at STP}}{C_p(CH_4) \text{ at STP}}\right)$
1300	0	0	1300	-19.05 ± 0.05	-	0.815
1000	391.88	200	1300	-19.05 ± 0.05	0.701	
1000	426.80	220	1300	-19.05 ± 0.05	0.694	
1000	465.12	240	1300	-19.05 ± 0.05	0.693	
1200	391.88	200	1300	-19.05 ± 0.05	0.701	
1200	426.80	220	1300	-19.05 ± 0.05	0.694	
1200	467.54	240	1300	-19.05 ± 0.05	0.697	
1400	391.88	200	1300	-19.05 ± 0.05	0.701	
1400	427.77	220	1300	-19.05 ± 0.05	0.699	
1400	469.00	240	1300	-19.05 ± 0.05	0.696	
					$\bar{F}=(0.697 \pm 0.005)^{(*)}$	

(*) Including the effects of errors associated with the O_2- and CH_4-flowrate indications, the final value of the conversion factor becomes 0.697 ± 0.020. This value should be compared with F = 0.69 listed by the flowmeter manufacturer.(4)

TABLE III.- SUMMARY OF RESULTS FOR ACETYLENE FLOWMETER CONVERSION FACTOR

Air-Flowrate (ℓ) cm^3/min (True Reading)	O_2-Flowrate (m) cm^3/min (True Reading)	CH_4-Flowrate (n) cm^3/min (Dial Reading)	Sample Gas Flowrate cm^3/min (Air Equivalent)	O_2-Partial Pressure Monitor Output (mV)	C_2H_2 Conversion Factor (F)	Theoretical Value(4) $\left(\frac{C_p(\text{Air})\text{ at STP}}{C_p(C_2H_2)\text{ at STP}}\right)$
1300	0	0	1300	-19.05 ± 0.05	-	0.656
1000	426.80	200	1300	-19.05 ± 0.05	0.648	
1000	470.45	220	1300	-19.05 ± 0.05	0.649	
1000	508.28	240	1300	-19.05 ± 0.05	0.643	
1200	426.80	200	1300	-19.05 ± 0.05	0.648	
1200	470.45	220	1300	-19.05 ± 0.05	0.649	
1200	509.25	240	1300	-19.05 ± 0.05	0.644	
1400	426.80	200	1300	-19.05 ± 0.05	0.648	
1400	471.42	220	1300	-19.05 ± 0.05	0.650	
1400	508.28	240	1300	-19.05 ± 0.05	0.643	
					$\bar{F}$=(0.644±0.005)(*)	

(*) Including the effects of errors associated with the O_2- and C_2H_2-flowmeter indications, the final value of conversion factor becomes 0.644 ± 0.020. This value should be compared with F = 0.67 listed by the flowmeter manufacturer.(4)

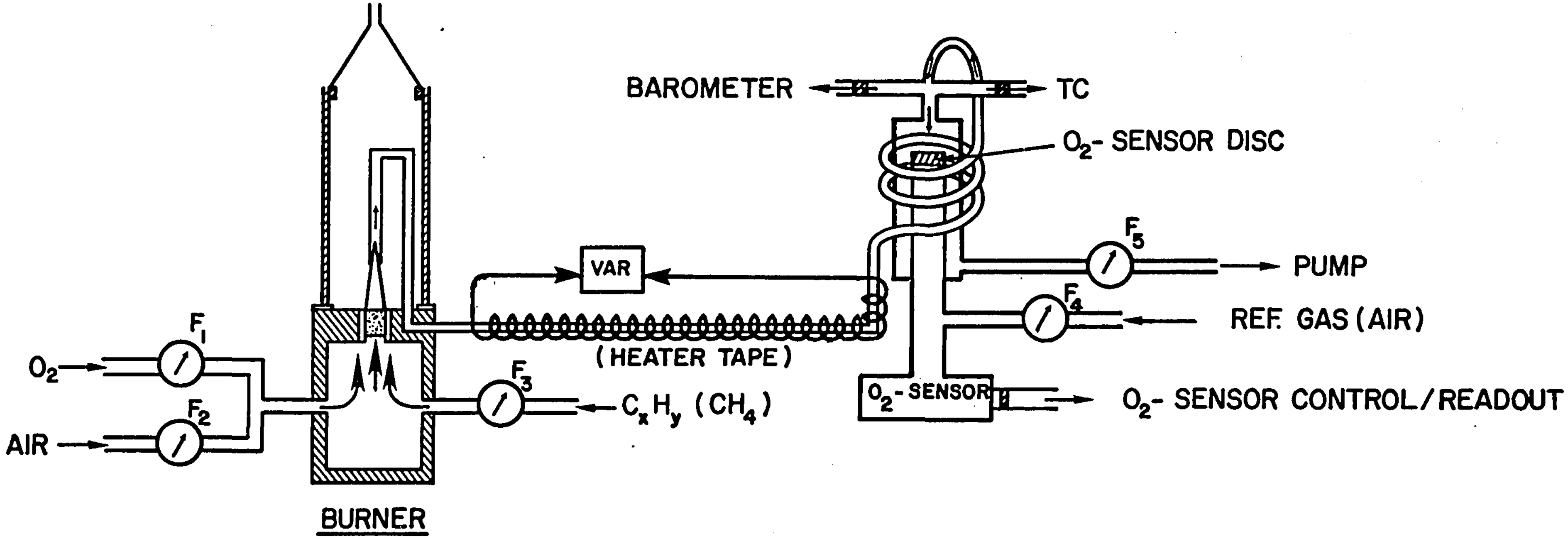

FIGURE - 1. SCHEMATIC DIAGRAM OF THE EXPERIMENTAL SYSTEM FOR MONITORING OXYGEN PARTIAL PRESSURE IN HYDROCARBON COMBUSTION PRODUCT GASES.

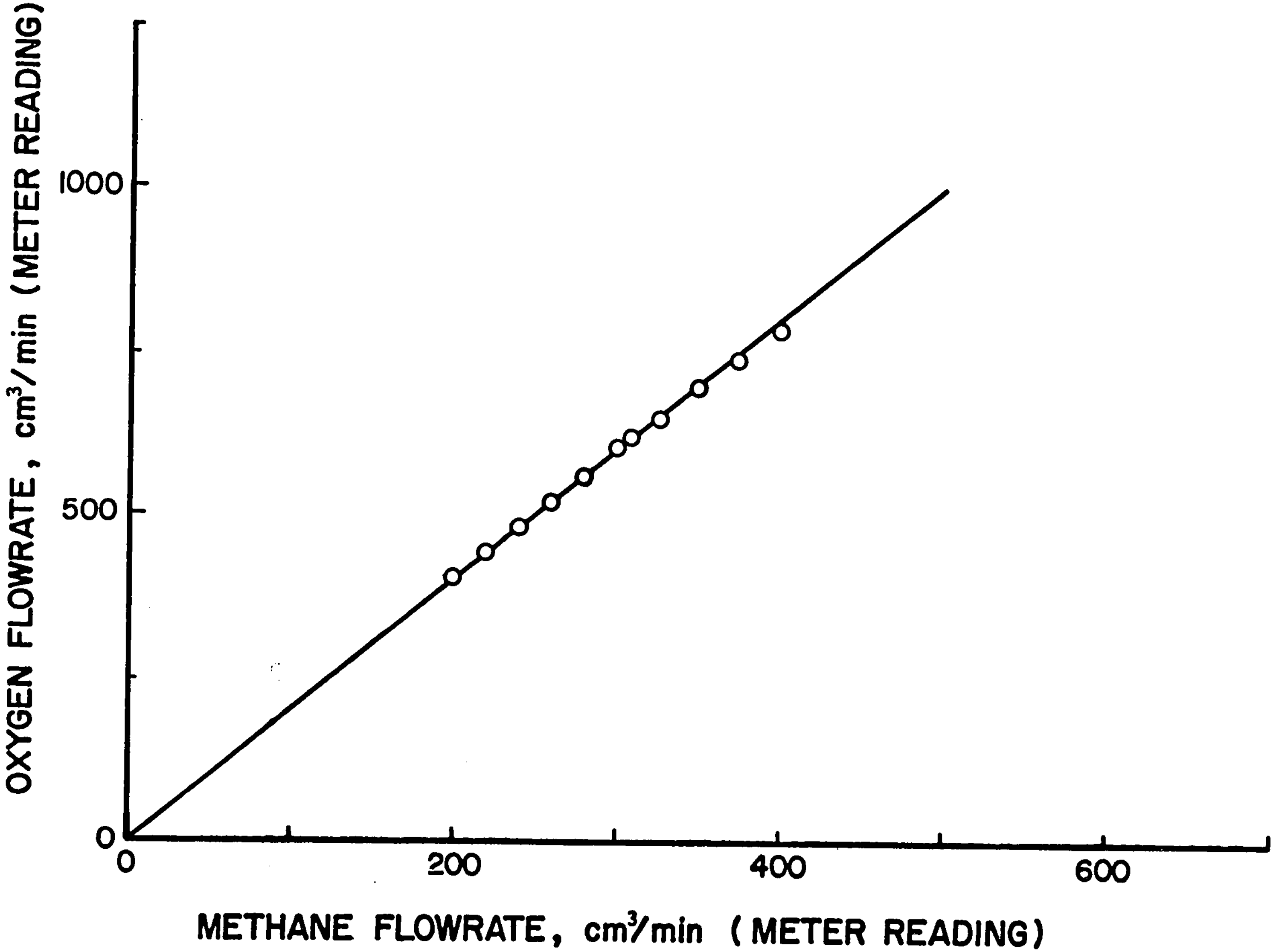

FIGURE - 2(a). METHANE FLOWRATE vs OXYGEN FLOWRATE FOR MAKING $X(O_2)$ IN THE COMBUSTION PRODUCTS EQUAL TO THAT IN NORMAL AIR.

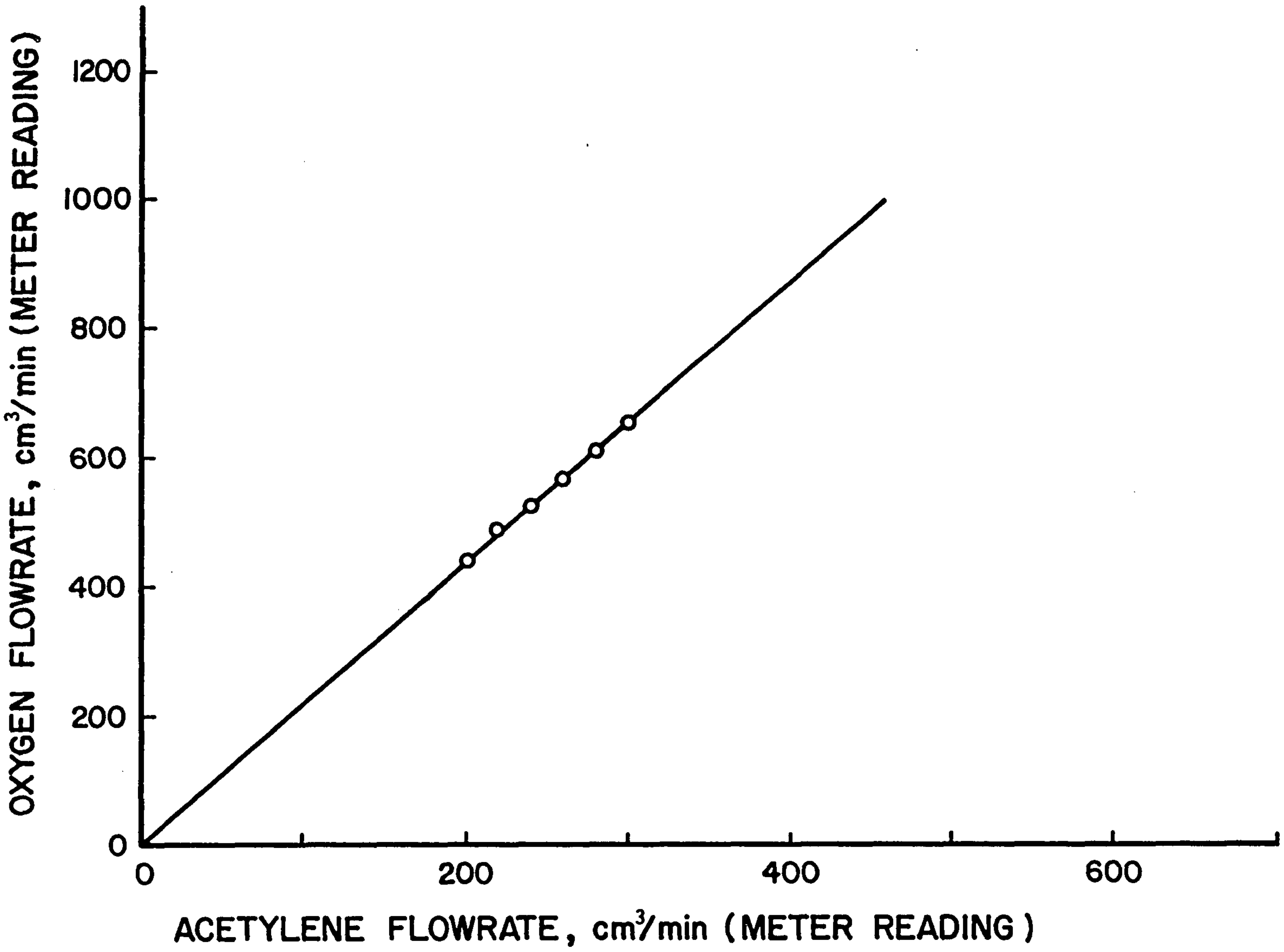

FIGURE - 2 (b). ACETYLENE FLOWRATE vs OXYGEN FLOWRATE FOR MAKING X(O_2) IN THE COMBUSTION PRODUCTS EQUAL TO THAT IN NORMAL AIR.

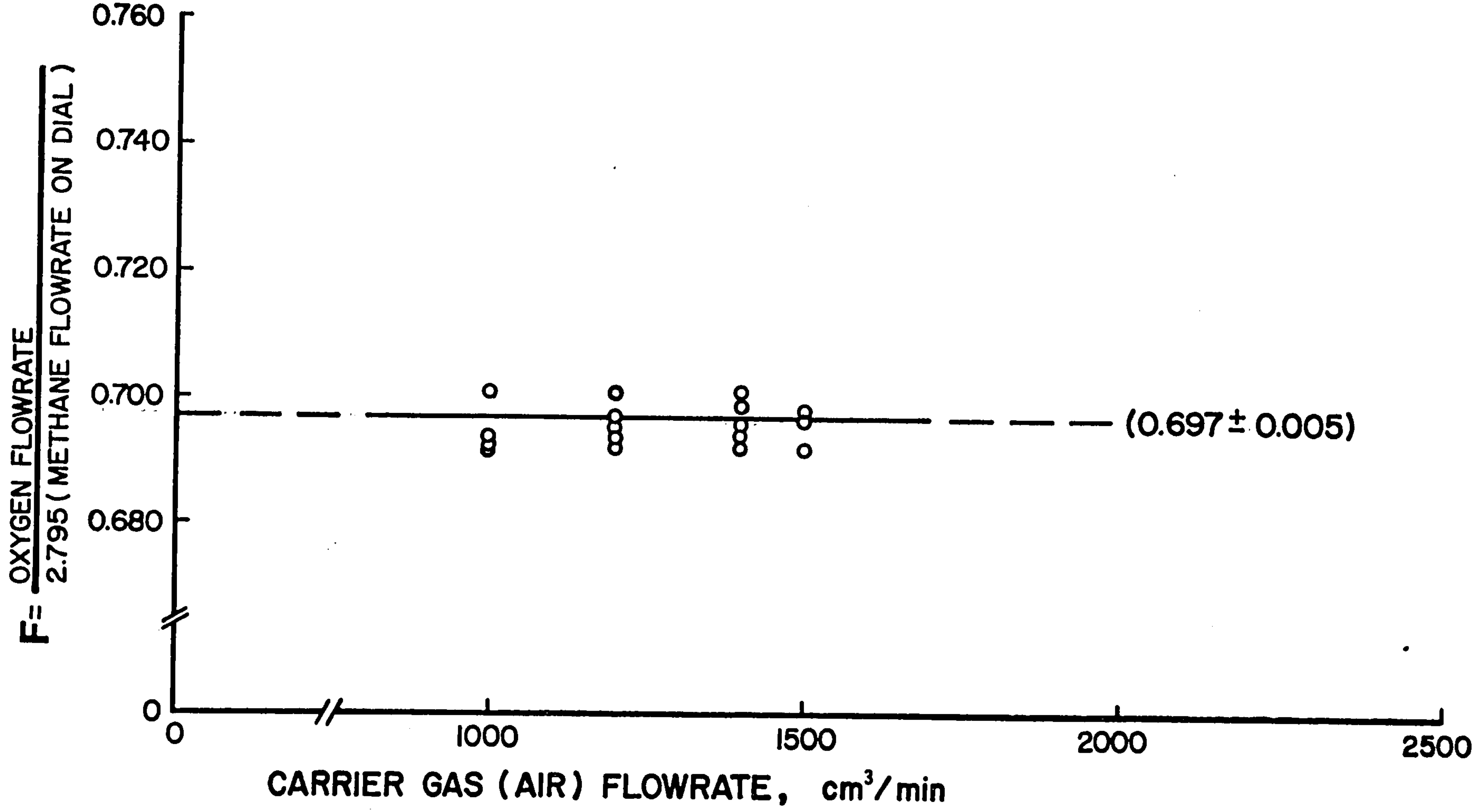

FIGURE - 3(a). DEPENDENCE OF METHANE CONVERSION FACTOR, F , FOR THERMAL MASS FLOWMETERS ON THE CARRIER GAS (AIR) FLOWRATES.

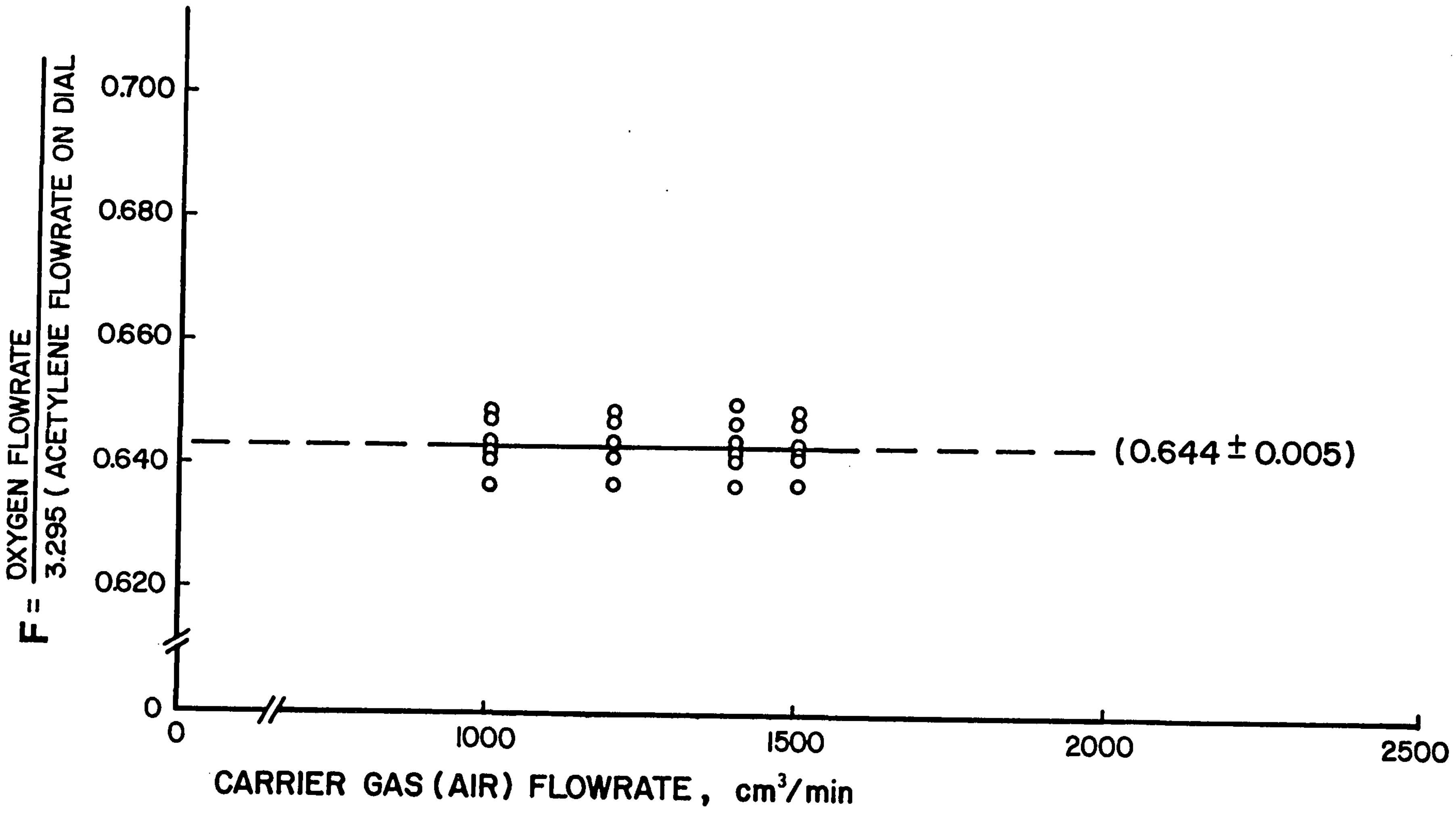

FIGURE - 3(b). DEPENDENCE OF ACETYLENE CONVERSION FACTOR, F , FOR THERMAL MASS FLOWMETERS ON THE CARRIER GAS (AIR) FLOWRATES.

1. Report No. NASA TM-85676	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle A New Technique for Measuring Gas Conversion Factors for Hydrocarbon Mass Flowmeters	5. Report Date August 1983 6. Performing Organization Code 505-33-53-14
7. Author(s) Jag J. Singh and Danny R. Sprinkle	8. Performing Organization Report No.
9. Performing Organization Name and Address Langley Research Center Hampton, VA 23665	10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	13. Type of Report and Period Covered Technical Memorandum 14. Army Project No.

15. Supplementary Notes

16. Abstract

A new technique for measuring calibration conversion factors for hydrocarbon mass flowmeters has been developed. It has been applied to a widely used type of commercial thermal mass flowmeter for hydrocarbon gases. The values of conversion factors for two common hydrocarbons measured using this technique are in good agreement with the empirical values cited by the manufacturer. Similar agreements can be expected for all other hydrocarbons. The technique is based on Nernst theorem for matching the partial pressure of oxygen in the combustion product gases with that in normal air. It is simple, quick and relatively safe--particularly for toxic/poisonous hydrocarbons.

17. Key Words (Suggested by Author(s)) Thermal Mass Flowmeters, Gas Conversion Factor, Hydrocarbons, Oxygen Partial Pressure, Zirconia-Sensor, Specific Heat at Constant Pressure	18. Distribution Statement Unlimited - Unclassified Subject Category 35

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 14	22. Price* A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161