NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3106

AN EVALUATION OF THE SOAP-BUBBLE METHOD FOR BURNING VELOCITY MEASUREMENTS USING ETHYLENE-OXYGEN-NITROGEN AND METHANE-OXYGEN-NITROGEN MIXTURES

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SUMMARY

A soap-bubble, constant-pressure method was used to measure laminar burning velocities of some hydrocarbon-nitrogen-oxygen mixtures. A nonaqueous bubble mixture was employed, and schlieren motion-picture photographs of the total flame sphere and the expanding bubble were taken with a high-speed motion picture camera. The burning velocity was calculated by dividing the linear rate of growth of the flame sphere radius by the theoretical expansion ratio.

An upper limit of spatial velocity measurement was found for the soap-bubble method. The limit was evidenced by the fact that the smooth flame spheres broke up into roughened surfaces, and the uniform rate of travel was replaced by an acceleration. For ethylene-oxygen-nitrogen mixtures, the flame front began to break up soon after ignition for spatial velocities of 2500 to 3500 centimeters per second. This behavior is believed to explain the reported difference between a burning velocity of methane and oxygen mixtures measured by the soap-bubble method and by the burner method. The bubble-method measurement was nearly 100 percent higher than the Bunsen measurement.

Burning velocities for some ethylene-oxygen-nitrogen and methane-oxygen-nitrogen mixtures richer in oxygen than air are reported. The methane velocities were lower than those measured by Singer and Heimel using a burner method and closer to the burner measurements of Jahn. The relative effects of oxygen concentration on the burning velocity of methane and ethylene as measured both by the soap-bubble method and by burner methods are comparable.

INTRODUCTION

Laminar burning velocity has been considered a fundamental property of combustible mixtures, and since it can be simplified as a one-dimensional steady-state problem, has been emphasized by the theorists

(ref. 1). In order to compare theory with experiment, however, it has been desirable to show that burning velocity measurements are independent of the experimental technique.

At the present time several methods are in use for the measurement of burning velocity: the flat-flame method, the constant-volume-bomb method, the constant-pressure-bomb method (soap-bubble technique), the tube method, the Bunsen burner methods, and the slot-burner method. In a recent review of the methods of measurement of burning velocity (ref. 2), it was pointed out that the measured laminar burning velocities for hydrocarbons in air are in better agreement among the various methods than for hydrocarbons in oxygen. In fact, recently reported burning velocities for ethylene-air mixtures at stoichiometric concentration measured in various laboratories by different techniques - the soap-bubble technique (refs. 3 and 4), the slot burner (ref. 5), the constant-volume bomb (ref. 6), a Bunsen burner method (schlieren) (ref. 7), and a modified-tube method (ref. 8) - agree quite well, as shown by the very narrow range of measured values from 62.3 to 64.0 centimeters per second. This comparison indicates that careful study and elimination of the sources of error in the various methods are leading to the reliable measurement of burning velocities for hydrocarbon-air flames. 3112

For faster-burning flames, the variation of measured burning velocities reported in the literature is much greater; for example, for methane-oxygen flames, a burner method (total cone height) gives 330 centimeters per second (ref. 9, p. 465), another burner method (frustrum) gives 445 centimeters per second (ref. 9, p. 467), while the soap-bubble method measurement was 620 centimeters per second (ref. 10).

In a preliminary investigation conducted at the NACA Lewis laboratory, the anomalously high burning velocities of faster flames measured by the soap-bubble method when compared with velocities measured by Bunsen burner methods were found to result from the fact that for faster flames (spatial velocities above 2500 cm/sec), the flame front becomes rough and the flame accelerates (ref. 11). It is obvious that these roughened flames are no longer comparable with laminar burner flames.

The purpose of the present investigation was to reexamine the use of the soap-bubble method for fast-burning flames, to compare burning velocities measured by this method with those of other methods reported in the literature, and to determine the upper limit of the soap-bubble method.

The soap-bubble method of measuring burning velocity originally devised by Stevens (ref. 12), used by Fiock and Roeder (refs. 13 to 15), and recently improved by Pickering and Linnett (ref. 16) and Strehlow (ref. 3) is essentially a constant-pressure-bomb method. A soap bubble is blown with a combustible mixture, the mixture is ignited at the center of the sphere by a spark, and the flame travel is recorded photographically. The linear rate of travel of the flame divided by the expansion

ratio of the hot gases is a measure of the fundamental burning velocity of the flame. (For a discussion of the theory of the method assuming zero flame front thickness, see the early work of Stevens in refs. 10 and 12. The effect of flame front thickness on burning velocity may be evaluated by means of the burning-velocity equation described in ref. 17).

In the present investigation, an improved soap-bubble method (ref. 3), using a nonaqueous film to reduce the effect of moisture and an inert atmosphere to prevent the effect of afterburning, was employed. Schlieren motion-picture photographs of the total flame and bubble spheres were used instead of the V-trace of the expanding flame used by previous investigators. Burning velocities for some methane-oxygen-nitrogen and ethylene-oxygen-nitrogen mixtures at atmospheric pressure and room temperature are reported.

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APPARATUS AND PROCEDURE

The general arrangement of the setup, similar to that used in reference 4, is shown in figure 1. The bubble chamber is shown in detail, including the firing column and the soap cup, in figure 2. An inert chamber atmosphere (argon) was used in some of the runs to prevent afterburning. Details of the firing column and the retractable spark gap are shown in figure 3.

In this method a combustible mixture is introduced through the mixture inlet tube (figs. 2 and 3) with the spark gap retracted into the firing column. The space from the side arm to the tip of the brass tube supporting the bubble is swept out with mixture just before the lip of the outer brass tube is immersed in the soap solution contained in the cup. The bubble is blown to a predetermined diameter (6 cm was used for most measurements, 10 cm for visual observation of flame character); then the spark gap is lowered into the center of the bubble. The mixture is ignited by a spark, and schlieren photographs of the flame and the expanding bubble are recorded.

Ignition system. - The mixtures were ignited by a capacitance spark fired by discharging a 0.01-microfarad condenser charged to 5500 volts. The electrodes were enamel coated copper wires - 0.52 millimeter in diameter (U.S. No. 24 gage wire).

The firing of the spark was synchronized with the operation of the motion-picture camera in such a manner that ignition would occur near the peak camera speed. In order to ensure that the spark energy used in this investigation had no effect on the spatial velocity, the spark energy was reduced by a factor of 100 by using a 0.0001-microfarad condenser. For an ethylene-oxygen-nitrogen mixture (102 percent stoichiometric, $\alpha = O_2/(O_2 + N_2) = 0.400$), the spatial velocities measured using the reduced spark energy agreed favorably with values obtained at the higher spark energy.

Schlieren system and photographic record. - Schlieren photographs of the process were taken using the Z-type, two-mirror schlieren system shown in figure 1. The light source was an air-cooled BH-6 mercury lamp connected to a d-c power supply. The mirrors were 12 inches in diameter. The knife edge was in a horizontal position for all the burning velocity measurements, but was in a vertical position for some of the photographs used for observation of the flame surface. Magnification was determined from an image of a known distance on the film. The camera was a 16 millimeter Fastax camera with a booster giving a maximum camera speed of 7000 frames per second. The timing light was operated at 800 flashes per second. Eastman Super XX or Linagraph Ortho film was used.

Two typical schlieren photographic records are shown in figure 4(a) for a relatively fast burning mixture (spatial velocity $S_t \approx 2000$ cm/sec; 102 percent stoichiometric ethylene-oxygen-nitrogen; $\alpha = 0.400$) and in figure 4(b) for a slower burning mixture ($S_t = 520$ cm/sec; near stoichiometric ethylene-air).

Some shadowgraph records were taken by removal of the knife edge. Figure 5 shows a typical run ($S_t \approx 2000$ cm/sec; 103 percent stoichiometric ethylene-oxygen-nitrogen; $\alpha = 0.400$).

Bubble mixtures. - A nonaqueous bubble mixture developed in reference 18 was used. The mixture was 8 to 10 percent Alrosol cs (a synthetic nonaqueous detergent) in glycerine (c.p. grade). For some of the photographs planned for visual study, an aqueous mixture (ref. 14) consisting of 1 part triethanolamine oleate, 32 parts distilled water, and 8 parts glycerine was used as the bubble mixture. This mixture gives clearer photographs and is more stable for large bubbles.

Combustible mixtures. - Ethylene and methane were tanked gases. The manufacturer's purity for ethylene was 99.5 percent and for methane, 99.0 percent. Tanked mixtures of oxygen and nitrogen, used to obtain oxygen concentrations higher than in air, were labeled by the supplier to be accurate to ± 0.1 mole percent. Air from the room was passed through a drying tube containing anhydrous calcium sulfate. Combustible mixtures were made up by a partial-pressure method and were forced into the bubble by mercury displacement.

Analysis of Photographic Records

Burning velocity, as measured by the soap-bubble method, may be calculated from the following equation (refs. 3, 4, and 12):

$$V_b = S_t/E \tag{1}$$

where

V_b burning velocity

S_t spatial velocity

E expansion ratio, ratio of volumes of burned gas to unburned gas

The expansion ratio E may be determined experimentally and the burning velocity calculated from the following equation:

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$$V_b = S_t\left(\frac{r_o}{r_f}\right)^3 \tag{2}$$

where

r_o initial radius of sphere of unburned gas (soap bubble)

r_f final radius of sphere of burned gas

Alternatively, the expansion ratio may be calculated theoretically from the following equation:

$$E = \frac{n_F}{n_i}\frac{T_F}{T_i} \tag{3}$$

where

$\frac{n_F}{n_i}$ change in number of moles due to reaction, calculated from composition of initial mixture and equilibrium products for a constant-pressure adiabatic reaction

T_F flame temperature - equilibrium temperature for a constant-pressure adiabatic reaction

T_i initial temperature of mixture

The burning velocity may then be calculated from equation (1).

The spatial velocity is the rate of growth of the flame sphere, or the change in radius of the flame sphere with time. This velocity should be linear under constant-pressure conditions. In the determination of the spatial velocities, horizontal flame diameters were measured on the 16-millimeter film record using a traveling microscope and were plotted against frame sequence to give a typical record (fig. 6). The linear portion represents the smooth travel of the flame; the curved

portion results when the flame front nears the end of the combustible mixture and begins to slow down. The spatial velocity was determined from the slope of the rapidly rising linear portion illustrated in figure 6, the magnification factor, and the camera speed in number of frames per second:

$$S_t = 1/2PMC \tag{4}$$

where

S_t spatial velocity, or change in flame sphere radius with time, cm/sec

P slope of curve of flame diameter as measured on 16-millimeter film plotted against film frame sequence (fig. 6), cm/frame

M magnification factor; known distance divided by distance measured on film

C camera speed or number of frames per second determined by use of timing device, frames/sec

The initial radius of the sphere of unburned mixture, initial bubble radius, was determined by measurement of the bubble diameter shown in the first few frames of the photographic record (fig. 4).

RESULTS AND DISCUSSION

Evaluation of Soap-Bubble Method of Measurement

The major limitations of the soap-bubble method of measurement of burning velocity, which have been previously pointed out in references 3 and 9 (pp. 471-474), are:

(1) Bubble materials contaminate the combustible mixture.

(2) Some gases may react with the bubble material.

(3) Diffusion of gases through the soap bubble may change the composition of the mixture.

(4) Nonisotropic wave propagation results in nonspherical flame propagation for some mixtures.

(5) Convective rise of hot combustion gases complicates the measurement of slow burning velocities.

(6) Flame front has a finite thickness.

(7) Afterburning causes difficulties in final-radius measurements.

(8) High-frequency oscillations for fast flames have been observed by Stevens (ref. 19) and Strehlow and Stuart (ref. 3).

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(9) Rough flames appear in some mixtures.

The first five limitations were minimized by the choice of the bubble material and the combustible mixtures. Glycerine soap solution reduces the contamination by water vapor.

Representative combustible mixtures were tested for the effect of diffusion through the bubble by measurement of the spatial velocity of mixtures fired at different delay times (time required to blow bubble and ignite mixture) from 10 to 45 seconds. After 25 seconds, the measured spatial velocities for the mixtures were within the experimental error of the measurement. Longer time intervals gave greater deviations. Comparison of water and glycerine soap solutions showed that the diffusion effect for hydrocarbon-air mixtures is less for glycerine bubbles. A glycerine soap solution was used for all velocity measurements, and the bubbles were fired within a time delay of 15 seconds.

According to the work of reference 20, rich mixtures of methane-air and both lean and rich mixtures of ethylene in air propagate isotropically in the spherical bomb. In all cases isotropic propagation occurred when the fuel and air were of equal molecular weights or when the deficient component of the mixture - either fuel or air - was the component of higher molecular weight. These conditions were observed in the present work and no photographs showing nonisotropic propagation were used for measurement.

Only burning velocities faster than 60 centimeters per second were measured, and the convective effect did not appear to be important for these velocities.

The effect of neglecting the finite thickness of the flame front on the calculation of burning velocity may be evaluated by means of the relations developed in reference 17. It was concluded that for the sizes of flame spheres studied in the present investigation, the assumption of negligible flame thickness was justified.

The final radius of the sphere of burned mixture r_f is, as pointed out in reference 2, the most difficult measurement to make experimentally, and the errors are magnified because the radius is cubed in the calculation of burning velocity (eq. (2)). This measurement is difficult for two reasons: (a) The burning rate slows down as the flame front approaches the last of the unburned mixture, and (b) the final size continues to increase slowly. In oxygen-deficient mixtures, the final size is enhanced by diffusion of oxygen into the partially burned gases and continued reaction. This effect is called afterburning. Even in an inert atmosphere, the flame sphere continues to grow as a result of the temperature, pressure, and velocity gradients which exist. 3112

In the soap-bubble burning velocity measurements made in reference 4, the end point, or final diameter, was determined as an indentation in the V-trace photograph which occurred before afterburning began, but this point was very difficult to identify on schlieren photographs. To overcome this difficulty (ref. 3), the diameter was measured as a function of time as in figure 6 and the portion representing the slow expansion of the sphere was extrapolated back to the intersection with the rapidly expanding portion. The intersection of the two linear segments was used as the final diameter. Neither of these methods corrects for the flattening of the flame sphere shown in figure 4. In reference 3, inert gas, argon, also was used outside the bubble to reduce the error due to afterburning. In the present investigation, the expansion ratio was experimentally determined for the soap bubble in atmospheres of both argon and air. Ethylene-air mixtures as well as ethylene-oxygen-nitrogen mixtures with an α of 0.395 were studied. The experimental results are compared with the theoretical results in the following table:

Ethylene, percent	$\alpha = \frac{O_2}{O_2 + N_2}$	Gas outside bubble	$^aE_{ex}$ (experimental)	E_t (theoretical)	$\frac{E_{ex}}{E_t}$
6.64	0.21	Air	8.43	8.10	1.04
6.53	.21	Argon	8.09	8.06	1.00
12.17	.395	Air	11.65	10.41	1.12
12.08	.395	Argon	10.69	10.39	1.03

[a]Average value.

This work is in agreement with that of reference 3 and shows again that the expansion ratio is reduced by the presence of argon outside the bubble. Also, this measured expansion ratio is within the experimental error of the theoretical expansion ratio. In reference 9 (p. 479), it has previously been shown that for the case of the constant volume bomb the flame radius calculated from thermodynamic considerations agreed within about 1 percent of the observed flame radius throughout the explosion. Because of the experimental uncertainty in the determination

of the expansion ratio and because expansion ratios measured under the most favorable conditions (afterburning reduced by use of argon outside the soap bubble) were within the experimental error of the theoretical value, the theoretical expansion ratio was used to calculate the burning velocity.

It was observed that fast-burning flames were disturbed by high-frequency oscillations when a bubble chamber 12 by 12 by 12 inches was used. These oscillations were eliminated by using a larger chamber, 24 by 24 by 24 inches.

The final limitation cited, the occurrence of rough flames, was found to be very important. The first evidence of the effect appeared in the curves of flame diameter plotted against flame sequence for the faster flames. Figure 7 shows one record in which the flame appears to accelerate during the course of propagation. Examination of the flame photographs for this combustible mixture in 6-centimeter glycerine bubbles showed some evidence that the flame front was breaking up into a wrinkled surface. Clearer photographs were taken by using a water soap bubble initially 10 centimeters in diameter. The photographs in figure 8 show a flame changing from a smooth to a rough flame front. In this case, cone-like protuberances 3 to 4 millimeters in length appear on the flame surface after the diameter of the flame sphere is about half its final diameter. The first roughening of the surface occurs before the bubble breaks. It was estimated that for one flame the surface area of the rough flame sphere is approximately 1.5 to 2 times that of a smooth surface. This surface area was based on estimates of the average height, the average base diameter, and the total number of these cone-like protuberances on the flame surface. The final spatial velocity for this flame was about 1.5 times the initial spatial velocity of the smooth flame front.

It is probably the formation of the rough flame front which accounts for the previously observed difference in burning velocity of methane-oxygen flames measured by the soap-bubble method as compared with the Bunsen burner methods (ref. 11). This roughening would not have been apparent to investigators using the V-trace technique.

Some of the conditions under which rough flame spheres were observed are listed in table I. Both lean and rich mixtures of ethylene, methane, and pentane with atmospheres of various values of α gave rough flame surfaces. Qualitatively, the flame front appeared to become rough earlier in the run for the faster flames. Two sets of data for ethylene flames are recorded in table I. In one set, both the concentration of oxygen in the atmosphere and the ethylene concentration are changed to maintain the same stoichiometry; in the other, the oxygen concentration is held constant and the ethylene concentration is varied. With both kinds of changes, the burning velocity varies. The high

velocity limit for smooth flames appears to be near 2500 centimeters per second for both types of experiments. These experiments were carried out in a bubble 10 centimeters in diameter.

For flames in the spatial velocity range 2500 to 3500 centimeters per second, rough flame surfaces appeared near the end of the run. By using only the first linear portion of the curve of diameter against frame sequence to establish the spatial velocity, it is possible to measure the burning velocity for these faster flames. The reproducibility of the measurement is, however, less (approximately ±5 percent). For spatial velocities above 3500 centimeters per second, no satisfactory measurements could be made. 3112

The rough flame surface was not improved by using argon outside the soap bubble, by removal of the bubble chamber, or by reducing the ignition energy. The instability of the flame front may arise from the interaction of flame generated pressure waves reflected from the bubble-gas interface and the advancing flame front. George H. Markstein of the Cornell Aeronautical Laboratory and J. O. Hirschfelder of the University of Wisconsin have suggested that the roughened flame front may be a type of Taylor instability; such instabilities have been observed in liquid surfaces accelerated in a direction normal to their planes (ref. 21). The appearance of this rough flame surface limits the range of burning velocities which may be measured by the soap-bubble method.

Consistent values of spatial velocity and burning velocity may be obtained by means of the present soap-bubble technique when the precautions discussed are observed. For example, some spatial velocities for ethylene and air measured by this method are compared with those reported in the literature in table II. One mixture is fuel rich and the other is a near stoichiometric mixture. The reproducibility of the spatial velocities measured by this method is about ±3 percent. The reported measurements of spatial velocity agree quite well.

Burning velocities for stoichiometric mixtures of ethylene and air are compared in table III. The agreement among burning velocities measured by the soap-bubble method as used at various laboratories is very good. Burning velocities measured by all the methods except the burner method of reference 22 give comparable values. The latter measurement was made at 311° K and was reduced by an empirical equation to 298° K (ref. 22); therefore the comparison is not directly between two measured values. It is included in table III because burning velocities measured by this method for ethylene-oxygen-nitrogen mixtures are later compared with burning velocities obtained by the soap-bubble method.

Burning Velocities of Hydrocarbon-Oxygen-Nitrogen Mixtures

Burning velocities for ethylene-oxygen-nitrogen and methane-oxygen-nitrogen mixtures, richer in oxygen than air, and values previously reported in the literature for the same mixtures are listed in table IV. The burning velocities measured by the soap-bubble method are average values - the separate determinations are listed in table V. Hydrocarbon concentrations were chosen to be near the maximum burning velocity as measured by burner methods. In table IV these measured burning velocities are compared with values from the literature for the same mixtures. The burning velocities for methane-oxygen-nitrogen flames are lower than the velocities measured in reference 9 (p. 467) using a cone-frustrum method to calculate area of Bunsen flames. The velocities of the soap-bubble method are nearer the measurements of reference 9 (p. 465), also a Bunsen burner method but with cone areas calculated from the measured cone height.

The relative burning velocities for the three sets of measurements are compared in figure 9(a). Burning velocities at $\alpha = O_2/(O_2 + N_2) = 0.306$ and the methane concentration for maximum burning velocity were taken as the standard values for the two sets of data in the literature. Ratios of the burning velocities at other values of α to the standard values were then computed. For the soap-bubble burning velocities, the standard burning velocity was chosen as that at the same α, 0.306, and at the only concentration of methane studied, 107 percent of stoichiometric. Values of these ratios are plotted against α in figure 9; inasmuch as the points calculated from all three sets of data lie on a common curve, the relative effects of α on burning velocity measured by the three methods agree well.

The one ethylene-oxygen-nitrogen burning velocity measured by the soap-bubble method which can be compared directly is lower by 10 percent than the Bunsen burner value measured in reference 22. A schlieren image, total-area method, was used for the burner measurement. Ratios of burning velocity to standard burning velocity, calculated as described previously, are plotted against α in figure 9(b). The relative effects of α on burning velocity measured by the two methods are comparable.

In reference 22, the maximum measured burning velocities for the region of oxygen concentration α from 0.18 to 0.35 are compared with the relative effects of α on burning velocities predicted by the Semenov and by the Tanford and Pease equations for burning velocity. The agreement was quite good. Since the relative burning velocities agree for the two experimental methods, the relative values predicted by the equations would be equally good for soap-bubble burning velocities in the same range.

SUMMARY OF RESULTS

The results of this study of the soap-bubble method of laminar burning velocity measurement for methane-oxygen-nitrogen and ethylene-oxygen-nitrogen mixtures may be summarized as follows:

1. Measurements of burning velocity for stoichiometric ethylene-air mixtures made by the soap-bubble method using a nonaqueous bubble mixture, schlieren motion-picture photography, and the theoretical expansion ratio are in good agreement with measurements by other investigators using the soap-bubble method, the slot-burner method, Bunsen burner methods, the constant-volume-bomb method, and a tube method. 3112

2. The lack of agreement between burner-method and soap-bubble-method measurements of the burning velocity of methane-oxygen flames as reported in the literature is attributed to the high velocity limit of the soap-bubble method, which was evidenced in the present work by roughened flame fronts and accelerating flames.

3. The high velocity limit for the usefulness of the soap-bubble method was found for ethylene-oxygen-nitrogen mixtures to be in the spatial velocity range of 2500 to 3500 centimeters per second.

4. Burning velocities measured by the soap-bubble method for some methane-oxygen-nitrogen and ethylene-oxygen-nitrogen mixtures richer than air in oxygen are reported and compared with burning velocities measured by the burner method.

5. The effect of oxygen enrichment on the relative burning velocity as measured by the soap-bubble method for methane-oxygen-nitrogen and ethylene-oxygen-nitrogen mixtures is comparable with the effects measured by Bunsen burner methods.

6. When argon was used outside the bubble, the experimental expansion ratio was found to be closer to the theoretical expansion ratio.

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TABLE I. - OBSERVATION OF ROUGH FLAMES

Hydrocarbon	$\alpha = \frac{O_2}{O_2 + N_2}$	Percent stoichiometric	Approximate spatial velocity, S_t, cm/sec
C_2H_4	0.400	106	2000
C_2H_4	.554	103	3800
C_2H_4	.654	105	5500
C_2H_4	.749	107	6800
C_2H_4	0.554	59	1900
C_2H_4	.554	69	2300
C_2H_4	.554	87	2900
C_2H_4	.554	93	3300
C_2H_4	.554	103	3900
C_2H_4	.554	106	3900
CH_4	0.749	511	2500
CH_4	.749	77	2900
CH_4	.749	92	2950
CH_4	.749	102	3600
CH_4	.749	123	2900
C_5H_{12}	0.749	92	3000
C_5H_{12}	1.00	114	7000

TABLE II. - COMPARISON OF SPATIAL FLAME VELOCITIES FOR ETHYLENE-AIR MIXTURES MEASURED BY DIFFERENT INVESTIGATORS USING SOAP-BUBBLE METHOD

Ethylene, percent	Number of runs	Average spatial velocity, S_t, cm/sec	Technique	Gas outside bubble	Reference
7.70	5	520	Fastax camera	Air	Table V
7.68	8	521	Drum camera	Argon	3
6.53	4	503	Fastax camera	Argon	Table V
6.58	3	502	Drum camera	Air	4
6.53	10	484	Drum camera	Argon	3
6.64	7	497	Fastax camera	Air	Table V

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TABLE III. - COMPARISON OF BURNING VELOCITIES FOR STOICHIOMETRIC ETHYLENE-AIR FLAMES MEASURED BY DIFFERENT METHODS

Ethylene, percent	Burning velocity, S_t, cm/sec	Method	Reference
6.53	62.3	Soap bubble - argon	Table V
6.53	62.4	Soap bubble - argon	3
6.58	62.5	Soap bubble - air	4
6.54	63.1	Constant volume bomb	6
6.5	62.8	Bunsen burner	7
6.54	64.0[a]	NACA tube	8
6.54	74.0[b]	Bunsen burner	22

[a]Interpolated values on curve of burning velocity against concentration of ethylene in air.

[b]Measured value corrected for temperature from 311° to 298° K by method of ref. 22.

TABLE IV. - BURNING VELOCITIES FOR HYDROCARBON-OXYGEN-NITROGEN MIXTURES

CONTAINING MORE OXYGEN THAN AIR

Hydrocarbon	Percent stoichiometric	$\alpha = \frac{O_2}{O_2+N_2}$	Spatial velocity, S_t, cm/sec (average)	Theoretical expansion ratio, E_t	Burning velocity measurements, cm/sec			
					Soap-bubble method	Burner method Singer and Heimel (ref. 9, p. 467)[a]	Burner method Jahn (ref. 9 p. 465)[a]	Burner method Dugger and Graab (ref. 22)
Methane	107	0.306	766	8.92	85.8	112	80	
	106	.395	1215	9.72	125.0	168	126	
	107	.499	1906	10.49	181.7	225	171	
Ethylene	105	0.306	1331	9.49	140.2			154[b]
	105	.395	2021	10.41	194.1			
	107	.499	2921	11.35	257.4			

[a]Interpolated values from curves of maximum burning velocity against oxygen concentration.

[b]Interpolated value from curve of maximum burning velocity against oxygen concentration (values reduced from initial temperature of 311° to 298° K by empirical formula of ref. 22).

TABLE V. - SUMMARY OF BURNING VELOCITY MEASUREMENTS

BY THE SOAP-BUBBLE METHOD

Run	Hydrocarbon	$\alpha = \frac{O_2}{O_2+N_2}$	Percent stoichiometric	Atmosphere outside soap bubble	Spatial velocity, S_t, cm/sec	Theoretical expansion ratio, E_t	Burning velocity, V_B, cm/sec
1DD	Ethylene	0.21	102	Air	485		
2DD					494		
3DD[a]					510		
4DD[a]					495		
5DD[a]					493		
6DD[a]					495		
7DD[a]					508		
				Average	497	8.10	61.4
10DD	Ethylene	0.21	99	Argon	516		
11DD					492		
12DD[a]					499		
13DD[a]					506		
				Average	503	8.06	62.3
1W	Ethylene	0.21	119	Air	522		
2W					522		
3W					526		
4W					517		
5W					512		
				Average	520	----	----
1FF	Ethylene	0.306	105	Air	1296		
2FF					1321		
3FF					1340		
4FF[a]					1368		
5FF					1332		
				Average	1331	9.49	140.2
1II	Ethylene	0.395	105	Air	2024		
2II					1999		
3II					2036		
4II					2062		
5II					2010		
6II[a]					1984		
7II[a]					2033		
8II					2016		
				Average	2021	10.41	194.1

[a]Shadowgraph records.

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TABLE V. - Concluded. SUMMARY OF BURNING VELOCITY MEASUREMENTS

BY THE SOAP-BUBBLE METHOD

Run	Hydro-carbon	$\alpha = \frac{O_2}{O_2+N_2}$	Percent stoichio-metric	Atmosphere outside soap bubble	Spatial velocity, S_t, cm/sec	Theoret-ical expansion ratio, E_t	Burning velocity, V_B, cm/sec
12II	Ethylene	0.395	104	Argon	2005		
13II					2010		
14II					1968		
				Average	1994	10.39	191.9
1JJ	Ethylene	0.499	107	Air	2760		
2JJ					3123		
3JJ					2866		
4JJ					2804		
5JJ					3051		
9JJ[a]					2997		
				Average	2921	11.35	257.4
1GG	Methane	0.306	107	Air	758		
2GG					793		
3GG					778		
4GG					758		
5GG					743		
				Average	766	8.92	85.8
8HH	Methane	0.395	106	Air	1215		
9HH					1191		
10HH					1204		
11HH					1221		
12HH					1238		
13HH[a]					1220		
				Average	1215	9.72	125.0
1KK	Methane	0.494	107	Air	1969		
2KK					1899		
3KK[a]					1917		
7KK					1882		
8KK					1922		
9KK					1848		
				Average	1906	10.49	181.7

[a]Shadowgraph records.

CI-3 back 3/12

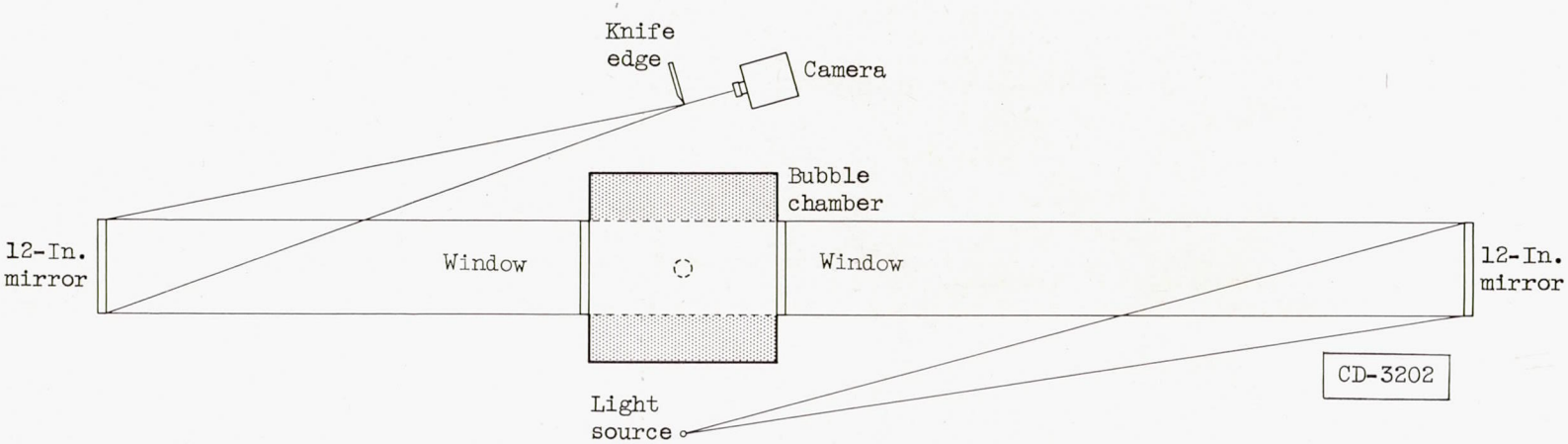


Figure 1. - General setup.

3112

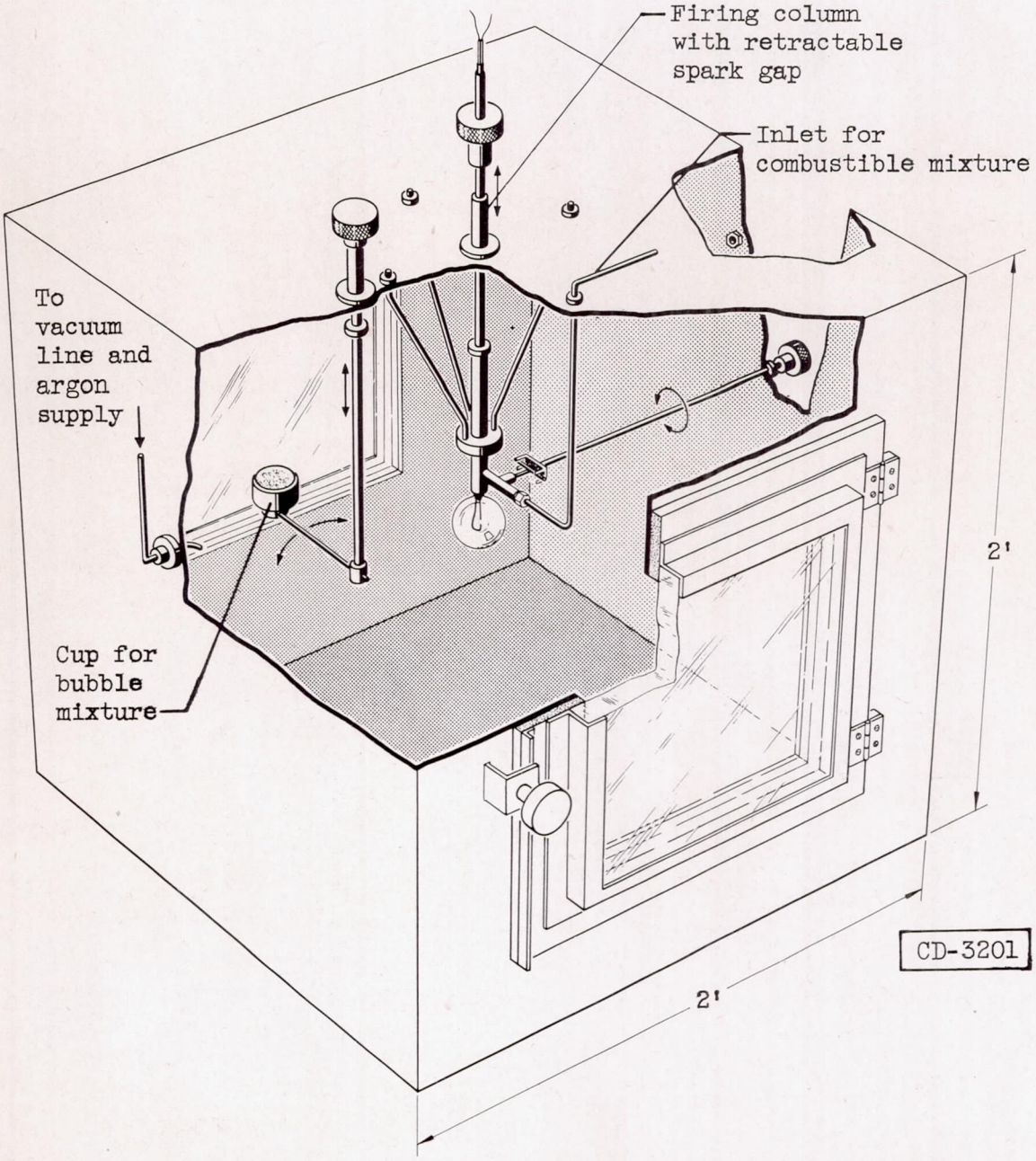


Figure 2. - Bubble chamber.

3112

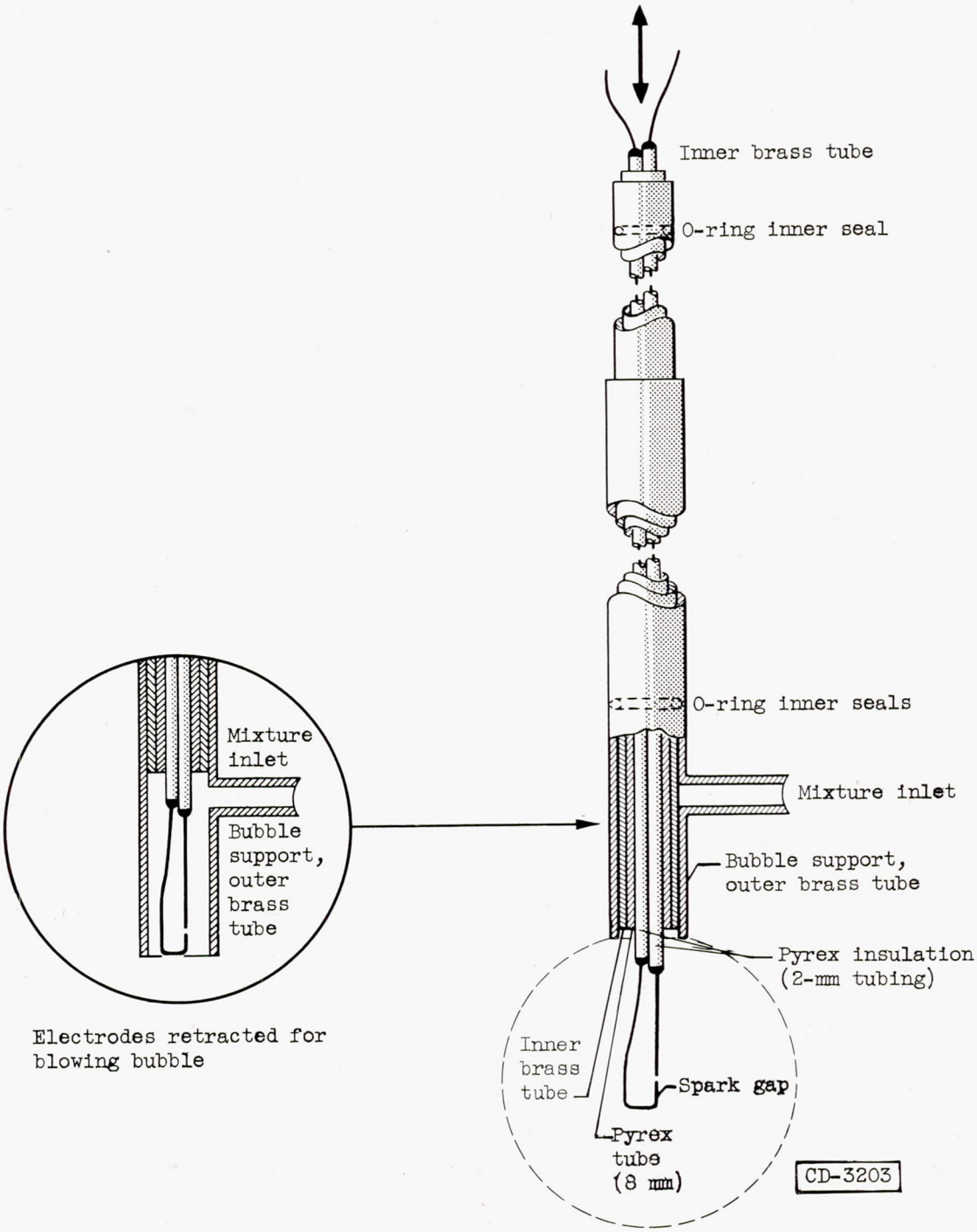
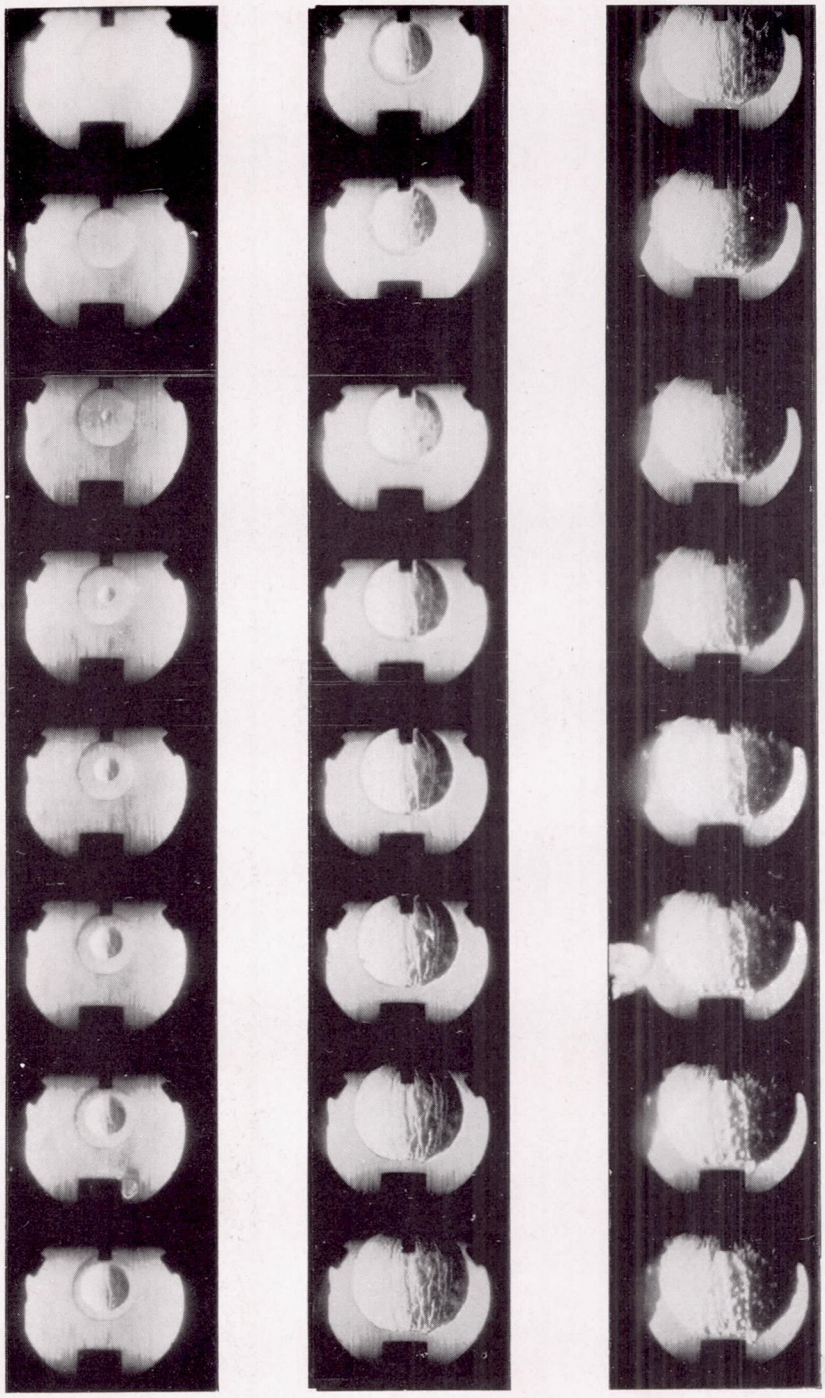


Figure 3. - Firing column with retractable electrodes.

3112

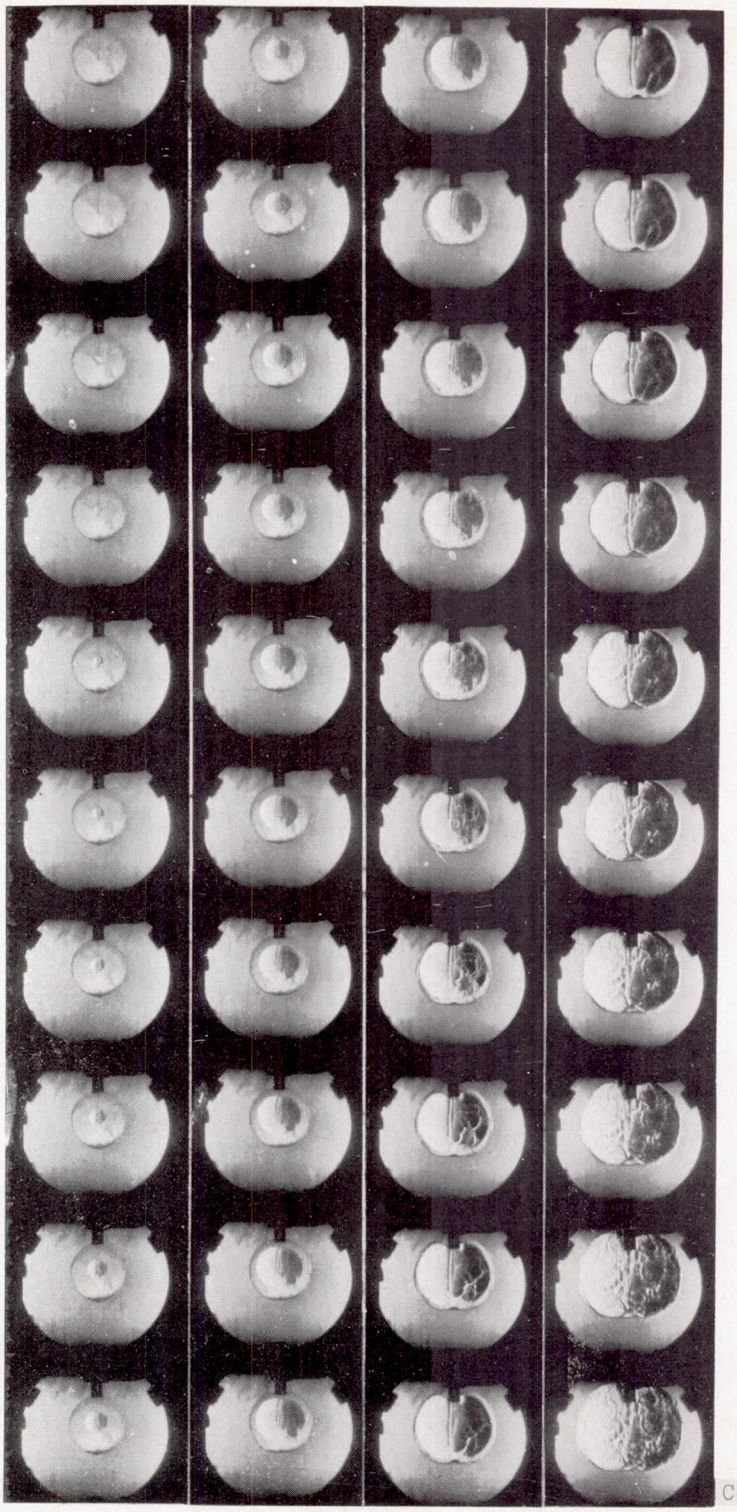


C-34286

(a) Relatively fast burning flame; spatial velocity, approximately 2000 centimeters per second.

Figure 4. - Typical schlieren motion-picture photographs.

3112



C-34287

(b) Slower burning flame; spatial velocity, 520 centimeters per second.

Figure 4. - Concluded. Typical schlieren motion-picture photographs.

3112

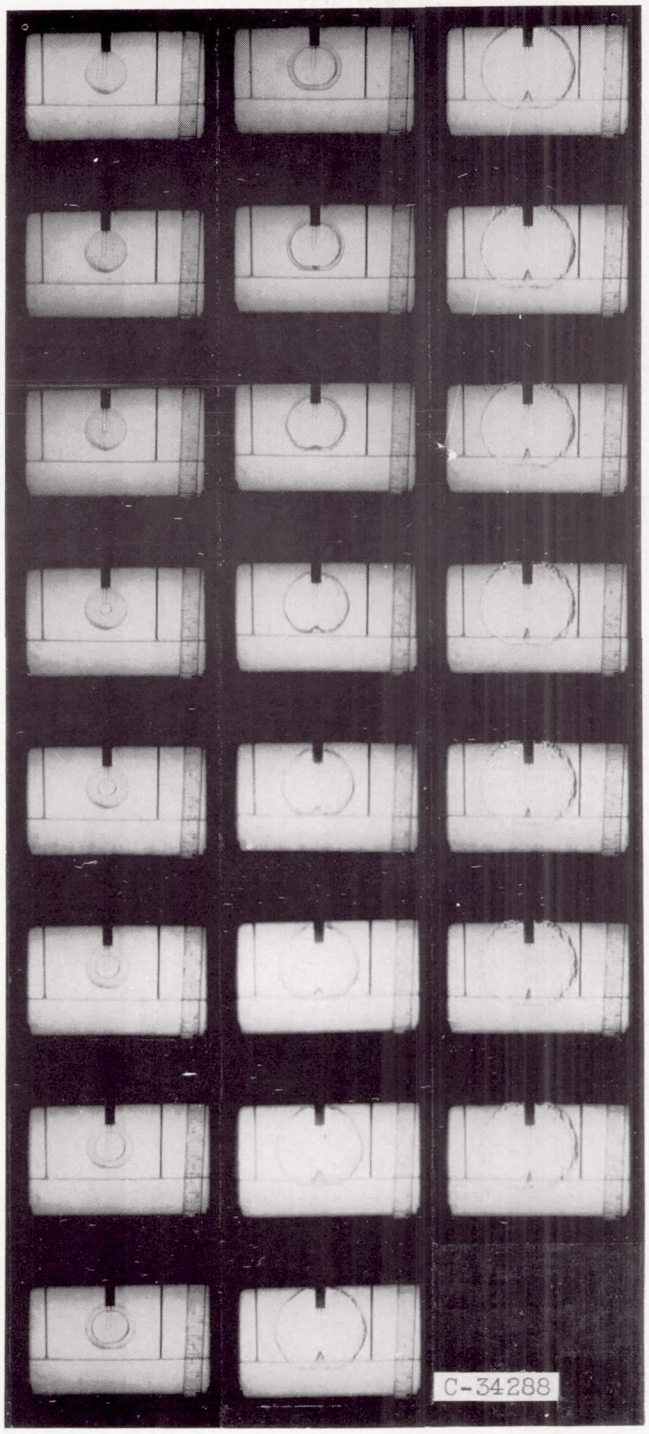


Figure 5. - Typical shadowgraph motion-picture photographs of flame propagating in combustible mixture.

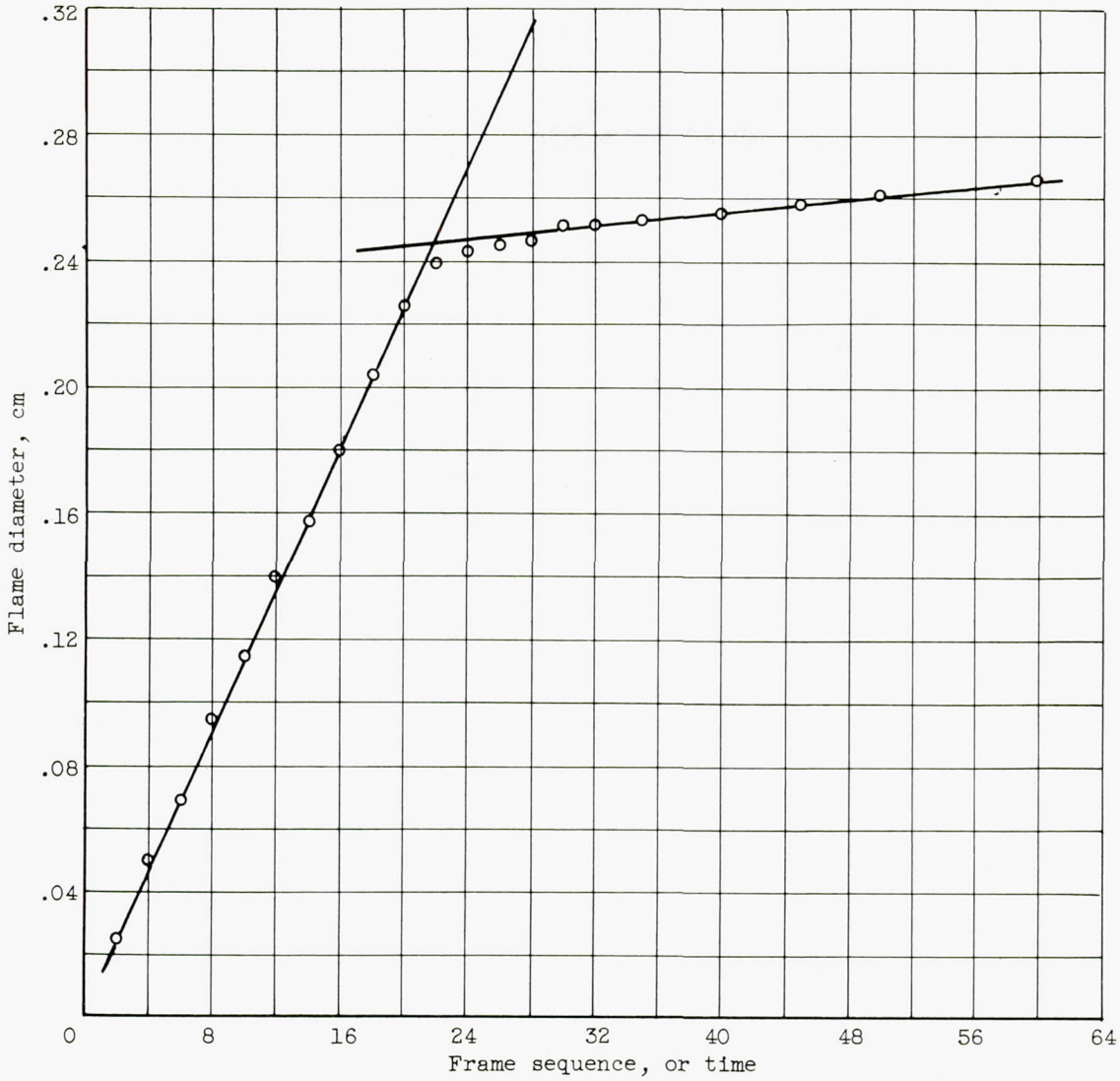


Figure 6. - Analysis of data to determine spatial velocity.

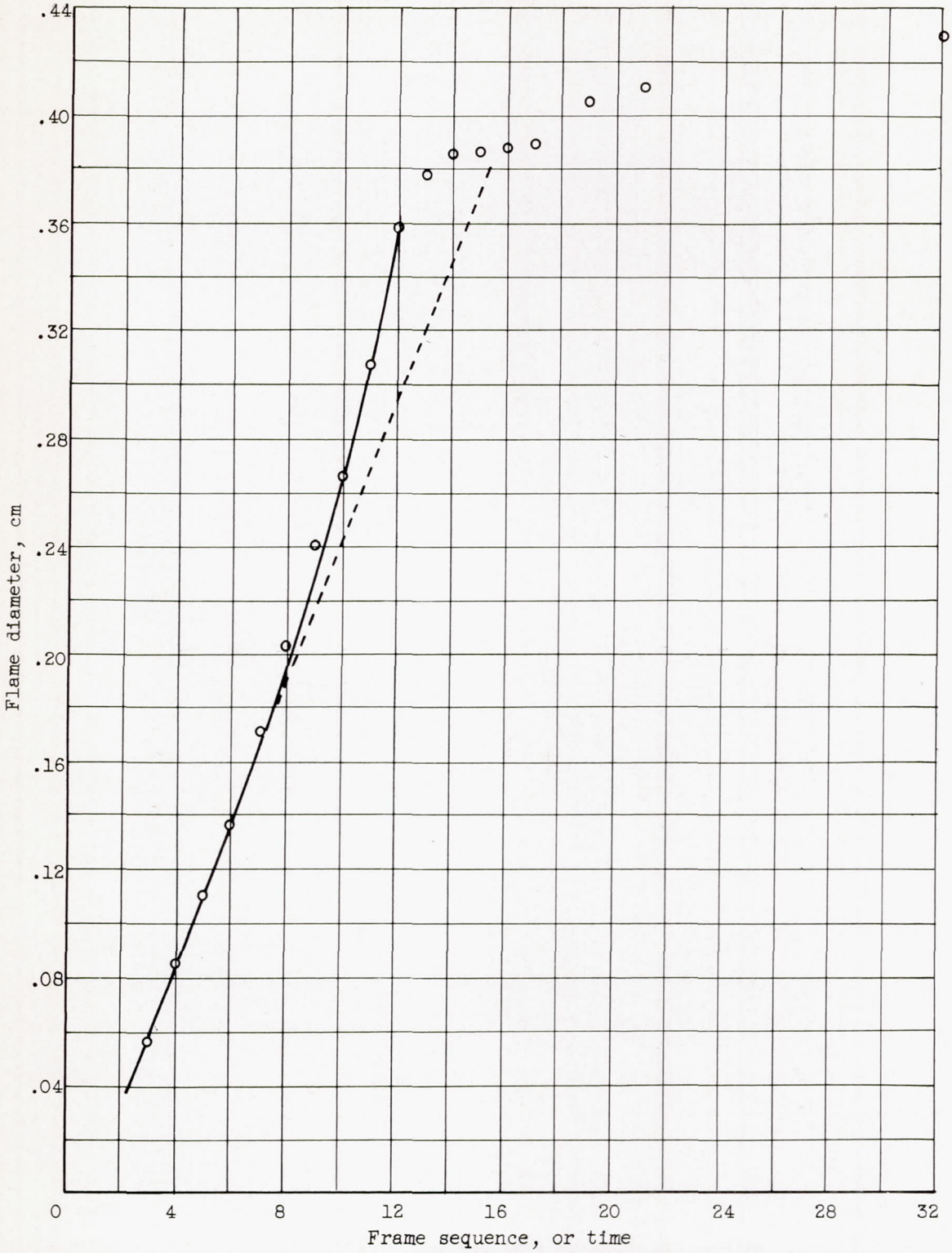


Figure 7. - Analysis of data to determine spatial velocity for rough flame.

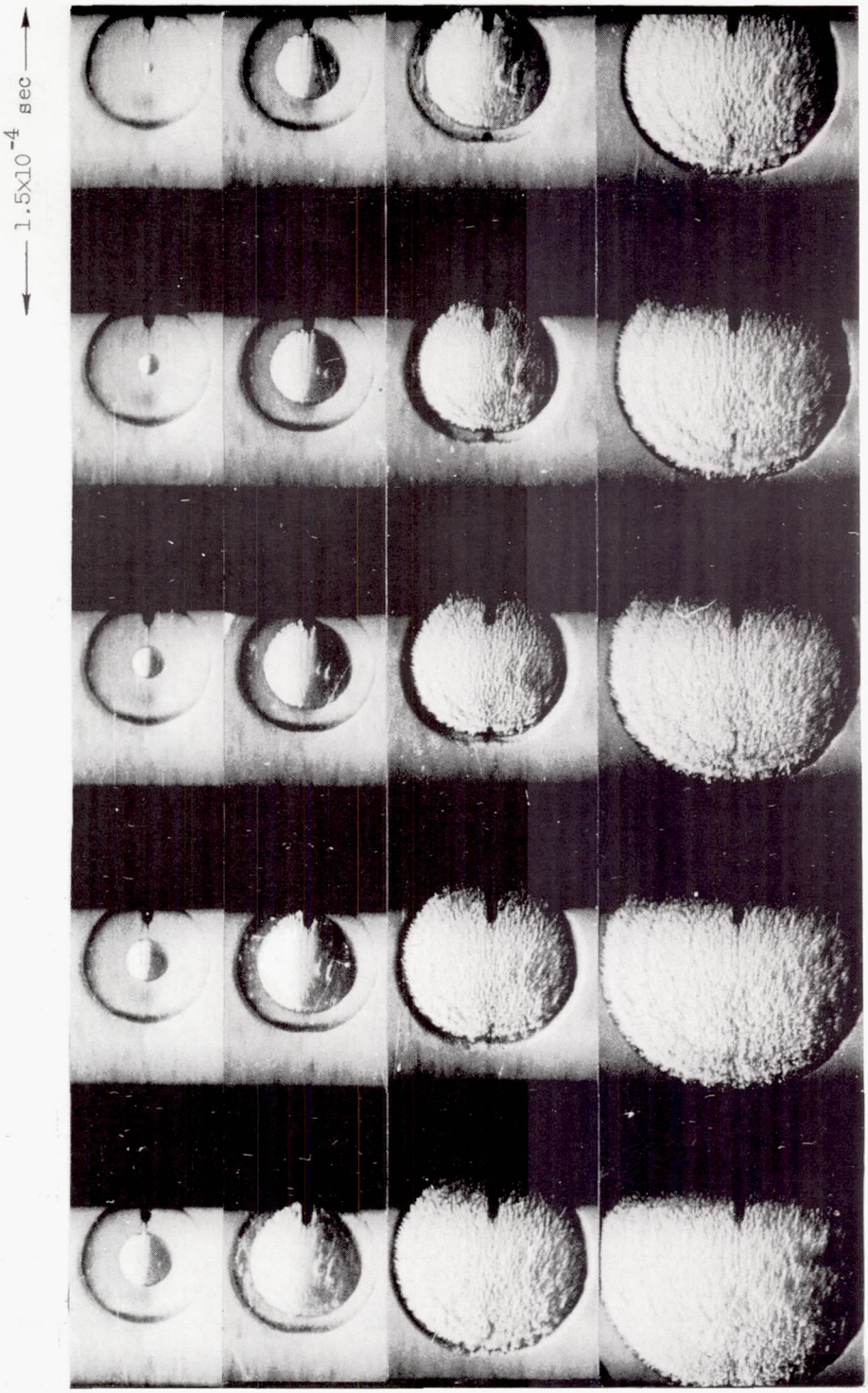
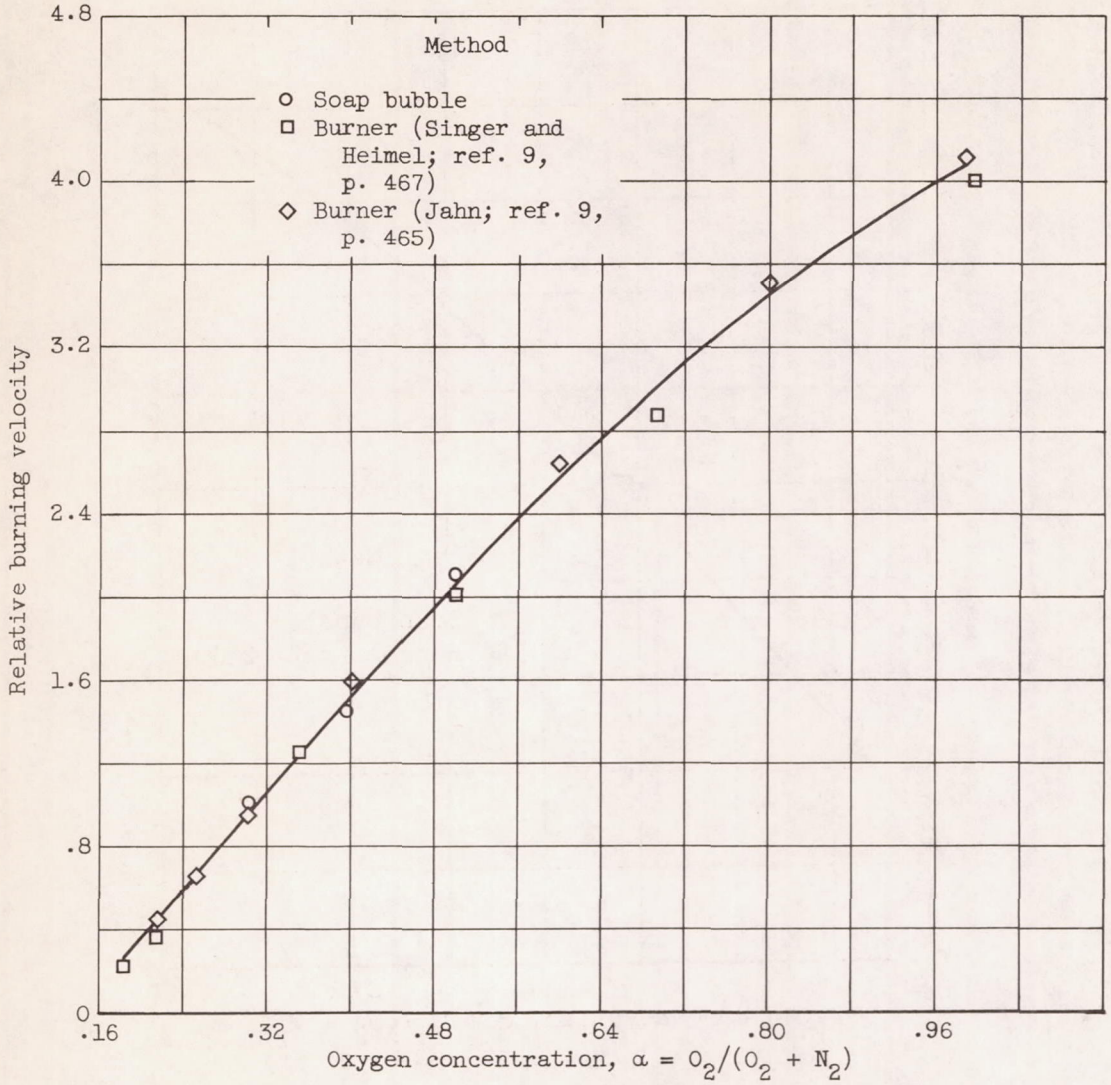


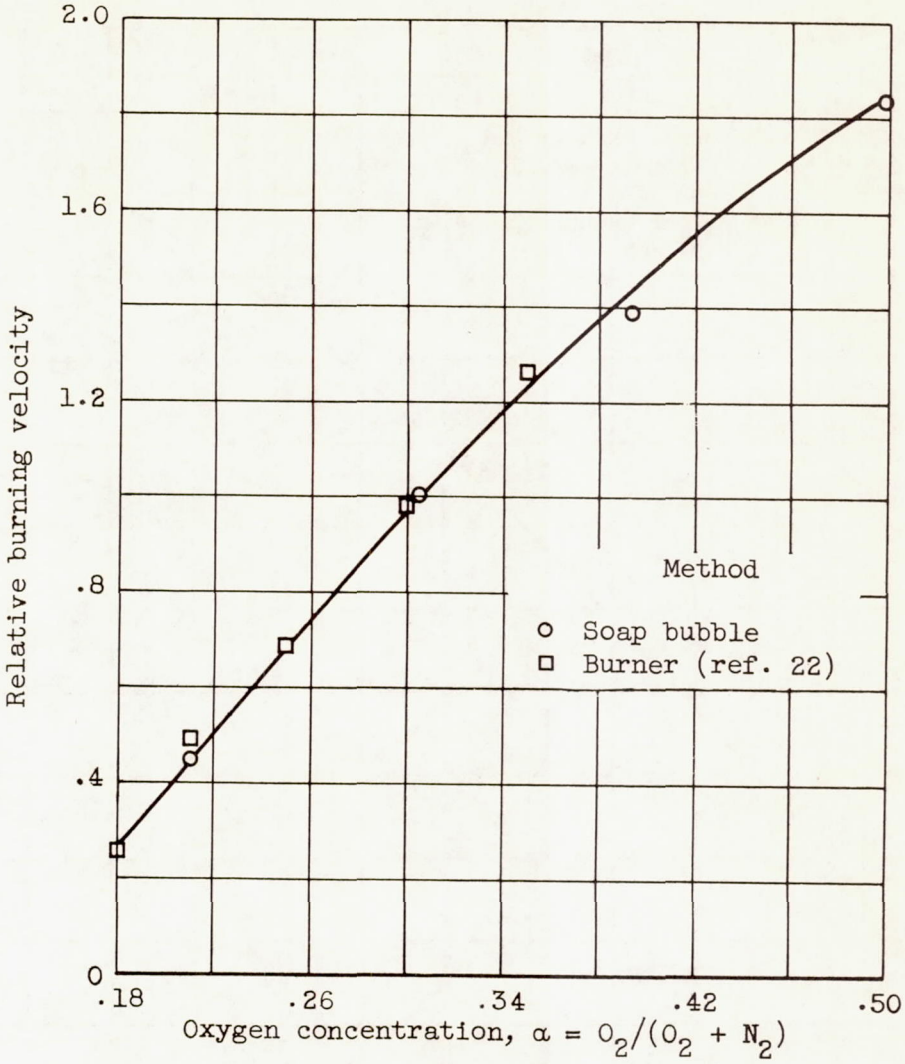
Figure 8. - Schlieren motion-picture photographs showing development of rough flame.

3112



(a) Methane-oxygen-nitrogen mixtures.

Figure 9. - Comparison of relative burning velocities.



(b) Ethylene-oxygen-nitrogen mixtures.

Figure 9. - Concluded. Comparison of relative burning velocities.