



# RESEARCH MEMORANDUM

SPARK IGNITION OF FLOWING GASES

IV - THEORY OF IGNITION IN NONTURBULENT AND TURBULENT  
FLOW USING LONG-DURATION DISCHARGES

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**NATIONAL ADVISORY COMMITTEE  
FOR AERONAUTICS**

WASHINGTON

August 19, 1954

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SUMMARY

A theory of spark ignition in nonturbulent- and turbulent-flowing homogeneous gases using long-duration discharges is presented. The theory is based on the concept that only a portion of the discharge length, a line source of ignition, is important in the ignition process. The theory contemplates a zone heated to flame temperature by the line source of ignition and of such size that the rate of heat generated in the zone equals the rate of heat loss from the zone. Theoretical and experimental comparisons of the energy in this heated zone reveal a relation among the variables total spark-discharge energy, gas density and velocity, electrode spacing, spark duration, intensity of turbulence, and fuel constants. The limited data available substantiate this relation.

INTRODUCTION

In order to provide information for the design and operation of jet-engine combustors, research is being conducted at the NACA Lewis laboratory to study the fundamental variables affecting the ignition and combustion of fuel-air mixtures. As part of this research, the parameters which may influence the energy required for a spark to ignite homogeneous fuel-air mixtures are being investigated.

The experimental investigations have shown that the energy required for a spark discharge to ignite a flowing propane-air mixture is markedly affected by gas velocity, pressure, spark duration, electrode parameters, and by a turbulence promoter placed upstream of the spark electrodes (refs. 1 to 3). Until the present time, no relation among the various parameters has been published. The two theories of ignition in quiescent gas mixtures that might possibly be considered in correlating these parameters are those of references 4 and 5. However, when these theories were applied to nonturbulent-flow data, it was found that the results did not correlate when either the total energy of the discharge or the highly concentrated energy contained in the cathode region of the discharge was

used. Also, in the case of turbulent-flowing gases, preliminary results showed that the total ignition energy did not correlate with the intensity of turbulence. These facts led to the belief that other considerations are necessary in the ignition of flowing gases.

The present investigation was undertaken to develop and evaluate a theory relating the various parameters of the spark discharge and the gas stream. The theory developed assumes that only a portion of the total energy supplied to the discharge is available for the ignition process. The theory has been applied to ignition data from references 1 and 2, which show the effect of pressure, velocity, spark duration, and electrode parameters. Turbulence data from reference 3 could not be applied in their present form; therefore, it was necessary to extend the investigation of the effect of turbulence on ignition energy. The results of this additional experimental work to determine the effect on ignition energy of known intensity and scale of turbulence are included in the appendix.

#### SYMBOLS .

The symbols used in this report are as follows:

A	Arrhenius constant
$c, c_1,$ $c_2, c_3$	constants
$c_p$	specific heat
E	energy of activation
$f(\sqrt{u^2}),$ $f'(\sqrt{u^2})$	functions of intensity of turbulence
H	total energy of spark discharge
$H_S$	spark energy in line source of ignition
$H'_S$	theoretical energy required to heat ignition zone to flame temperature
J	conversion factor, heat to electrical energy
k	thermal conductivity

$L_x$	longitudinal scale of turbulence
M	mesh size of turbulence promoter
$N_f$	mole fraction of fuel
$N_o$	mole fraction of oxygen
$P_{av}$	average power in total spark discharge
$P_s$	average power in line source of ignition
p	static pressure
Q	heat of combustion of fuel
R	gas constant
r	radius of heated zone caused by spark energy in line source of ignition
S	electrode spacing
$S_q$	quenching distance of quiescent mixtures
$T_f$	flame temperature
$T_o$	ambient temperature
t	time
$\sqrt{u^2}$	intensity of turbulence
V	stream velocity
x	distance from turbulence promoter to spark electrodes
$\theta$	spark duration
$\rho$	density

### THEORETICAL CONSIDERATIONS

#### Theories of Ignition in Quiescent Gas Mixtures

In references 4 and 5 there is considered a heated zone of critically small size which just satisfies the necessary condition for flame propagation that the rate of heat generated in the zone equals the rate of heat

loss from the zone. An excess enthalpy content of a plane combustion wave which, in the case of a heated zone of critical size, is the ignition energy, is defined in reference 4. This energy is determined by integration using quenching-distance and burning-velocity data, resulting in a relation among energy, quenching distance, and burning velocity. In reference 5, the analysis was simplified by certain assumptions, especially with respect to the rate of heat generated, so that the result is a relation between the flame temperature and minimum spark-ignition energy. Because of the somewhat simpler approach to the problem, the theory of reference 5 has been utilized in the development of the theory of ignition in flowing gases presented herein.

Assuming the heated zone left by a spark to be spherical in shape, the necessary condition for flame propagation (ignition) is expressed in reference 5 as

Rate of heat generated = rate of heat loss

$$\frac{4}{3} \pi r^3 A Q N_f N_o \rho^2 e^{-(E/RT_f)} = \frac{4 \pi r^2 k (T_f - T_o)}{cr} \quad (1)$$

The product  $cr$  is the thickness of the flame front or burning zone. Solving equation (1) for  $r$  gives

$$r = \sqrt{\frac{3k(T_f - T_o) e^{E/RT_f}}{c A Q N_f N_o \rho^2}} \quad (2)$$

This equation gives the critical size of the sphere.

The amount of heat  $H$  necessary to heat the critical sphere to flame temperature is

$$H = c_1 \frac{4}{3} \pi r^3 c_p \rho (T_f - T_o) \quad (3)$$

Or, upon substitution of  $r$ ,

$$H = \frac{c_2 k^{3/2} c_p (T_f - T_o)^{5/2} e^{3E/2RT_f}}{A^{3/2} Q^{3/2} N_f^{3/2} N_o^{3/2} \rho^2} \quad (4)$$

The analysis is based on a second-order reaction and diffusion processes are neglected.

The preceding analysis and equations are not directly applicable to the flowing-gas case, but certain modifications may be made based on a concept of a line source of ignition in flowing gases.

### Concept of Line Source of Ignition in Flowing Gases

Consider two electrodes placed  $S$  distance apart in a gas flowing at a velocity  $V$ , as shown in figure 1. At time  $t=0$ , a spark discharge is established between the electrodes. Under the influence of the gas stream, the discharge moves downstream at stream velocity (as deduced from data in ref. 6), so that at a time equal to  $t$ , the discharge is a distance  $Vt$  downstream. The discharge is considered to be in the shape of a square-cornered "u"; that is, rounding effects at the corners are neglected. At a time corresponding to the spark duration  $\theta$ , the discharge is at a distance  $V\theta$  downstream.

After passage of the discharge, there exists a heated zone larger in diameter than the discharge itself, but in a path coincident with that of the discharge. The vertical portion of the discharge moves at stream velocity so that the same volume of gas is being continuously heated, whereas the legs of the discharge lengthen with time, and cold gas is continuously being heated at the electrode ends of the discharge. Hence, it may be considered that the zone (fig. 1) surrounding the vertical portion of the discharge is at a much higher temperature and, therefore, constitutes a zone of ignition. This vertical zone, or line source of ignition, was used in the development of the theory of ignition of flowing gases presented herein.

The heated zone of the line source of ignition is moving at stream velocity and therefore, for the case of nonturbulent flow, may be considered as a heated zone in a quiescent mixture. This heated zone is then the same as that of reference 5, except that it is cylindrical in shape instead of spherical. Some considerations are made in the following section to account for the shape, the differences in spark duration, and the effects of turbulence.

### Determination of Theoretical Energy in Heated Zone

The process of establishing steady burning of a homogeneous fuel-air mixture from a long-duration discharge is visualized as follows: The line source of ignition is assumed to supply the heat necessary to raise the temperature of the heated zone to flame temperature; whereupon the initial flame continues to propagate, if the heated zone is of proper radius to fulfill the condition of rate of heat generated equal to or greater than rate of heat loss, and if the zone is of sufficient length. This length consideration is important, since at least a certain minimum

length is needed in conjunction with the proper radius in order to obtain flame propagation. If the length is too short, the ends of the heated zone will be quenched by the cool mixture before propagation can take place in the radial direction. The length of the heated zone under consideration should correspond to a length at least equal to the quenching distance  $S_q$  of quiescent mixtures. Therefore, if the energy is supplied from a line source of ignition of length  $S$  which is less than  $S_q$ , the energy must be considered as distributed over the length  $S_q$ . If the energy is supplied from a line source of length equal to or greater than  $S_q$ , then the heated zone must have a length equal to  $S$ . The equations are developed for the case where  $S$  is equal to or less than  $S_q$ , and then modified for the case where  $S$  is greater than  $S_q$ .

The amount of energy in the line source is considered to be the important factor in ignition. No heat losses from the heated zone either to the electrodes or to the gas are considered during the spark duration; also, no heat is considered to be supplied from any chemical reaction during this period.

Nonturbulent flow. - The equations for the rate at which heat is generated and for the rate of heat loss are the same as in equation (1) except for modifications to account for the cylindrical shape.

$$\text{Rate of heat generated} = \pi r^2 S_q c Q N_f N_o \rho^2 A e^{-E/RT_f} \quad (5)$$

$$\text{Rate of heat loss} = \frac{2\pi r S_q k (T_f - T_o)}{cr} \quad (6)$$

Equating (5) and (6) and solving for  $r$  gives

$$r = \sqrt{\frac{2k(T_f - T_o)}{c Q N_f N_o \rho^2 A e^{-E/RT_f}}} \quad (7)$$

which is the critical radius of the cylindrical heated zone.

The amount of heat  $H'_S$  (expressed as electrical energy by constant  $J$ ) necessary to raise the heated zone to  $T_f$  is

$$\begin{aligned} H'_S &= J \pi r^2 S_q \rho c_p (T_f - T_o) \\ &= \frac{2\pi J k S_q c_p (T_f - T_o)^2}{c Q N_f N_o \rho A e^{-E/RT_f}} \end{aligned} \quad (8)$$

This equation gives the theoretical amount of energy required to cause ignition in nonturbulent flow when the heated zone considered is that resulting from the line source of ignition.

Turbulent flow. - In the turbulent-flow case, the rate of heat loss depends upon the rate at which mass is transferred through the cylindrical surface of area  $2\pi rS$ , and the mass-transfer rate, in turn, depends upon the eddy-diffusion process taking place. Heat loss by mass transfer in the turbulent case supplants the heat loss by thermal conduction in the nonturbulent-flow case.

Two factors that control the eddy-diffusion process are the intensity and the scale of turbulence. When the scale of turbulence is large compared with the flame front thickness, as it is for the problem under consideration, the effect of scale on the rate of eddy diffusion is negligible compared with intensity of turbulence; hence, the effect of scale has been neglected in the following discussion.

The rate of heat loss depends upon the product of surface area, density, specific heat, temperature rise, and a velocity term. This velocity term is some function of the intensity of turbulence. The actual function has not been derived; hence the velocity is represented as some function of intensity, or  $f'(\sqrt{u^2})$ . The function involves the first power of  $\sqrt{u^2}$  in order to be correct dimensionally.

$$\text{Rate of heat loss} = 2\pi r S_q \rho c_p (T_f - T_0) f'(\sqrt{u^2}) \quad (9)$$

For ignition, equation (5) equals equation (9). Equating and solving for  $r$  gives

$$r = \frac{2c_p(T_f - T_0)}{Q N_f N_0 \rho A e} f'(\sqrt{u^2}) \quad (10)$$

The theoretical energy required to raise the heated zone to flame temperature under turbulent conditions is

$$\begin{aligned} H'_S &= J\pi r^2 S_q \rho c_p (T_f - T_0) \\ &= \frac{4\pi J S_q^3 c_p^3 (T_f - T_0)^3}{Q^2 N_f^2 N_0^2 \rho A^2 e} f'(\sqrt{u^2}) \end{aligned} \quad (11)$$

where  $f(\sqrt{u^2})$  is a new function of  $\sqrt{u^2}$ .

#### Relation Between Energy in Ignition Zone and Total Energy

Equations (8) and (11) express the energy requirements for ignition in terms of the energy supplied to the line source of ignition. Since experimentally, only the total energy supplied to the discharge can be measured, it is necessary to arrive at a relation between this energy and the line-source energy.

Two assumptions are made in the calculation of energy in the line source of ignition. The first assumption is that the total amount of energy in the discharge at any time varies linearly with time. Actually, the energy goes into the discharge somewhat more rapidly during the first part of the discharge; however, the assumption of uniform energy release is believed sufficiently accurate for use. The second assumption is that the power per unit length of discharge at any time is constant. In other words, regions of nonuniform dissipation of energy such as at the anode and cathode regions are not considered.

The average power  $P_{av}$  of the total discharge energy  $H$  is  $H/\theta$ , where  $\theta$  is the spark duration. This power is divided into two portions, which are the line source and the legs of the discharge. The relative amounts dissipated in each region depend upon the respective length of the legs and hence on time and gas velocity. The amount of power  $P_S$  that is available for the line source at any instant is

$$P_S = \frac{S}{2Vt+S} P_{av} \quad (12)$$

The energy of the line source  $H_S$  is the integral of this instantaneous power with respect to time taken over the discharge duration or

$$\begin{aligned} H_S &= \int_0^\theta P_S dt \\ &= \int_0^\theta \frac{S}{2Vt+S} \frac{H}{\theta} dt \\ &= \frac{HS}{2V\theta} \ln \frac{2V\theta+S}{S} \end{aligned} \quad (13)$$

Equation (13) relates the energy in the line source to the total ignition energy, the distance downstream of the discharge at the end of the discharge time, and the electrode spacing.

Theoretical Equations Expressed in Terms of Total Ignition Energy

For the nonturbulent-flow case, equating (8) and (13) gives

$$\frac{2\pi JkS_q c_p (T_f - T_0)^2}{cQN_f N_0 \rho A e \cdot -(E/RT_f)} = \frac{HS}{2V\theta} \ln \frac{2V\theta + S}{S}$$

or, nondimensionally,

$$\frac{4\pi J V \theta S_q k c_p (T_f - T_0)^2}{cHSQ N_f N_0 \rho A e \cdot -(E/RT_f)} = \ln \frac{2V\theta + S}{S} \tag{14}$$

Equation (14) holds when electrode spacing is less than quenching distance. When the electrode spacing is equal to or greater than the quenching distance, the equation is

$$\frac{4\pi J V \theta k c_p (T_f - T_0)^2}{cHQ N_f N_0 \rho A e \cdot -(E/RT_f)} = \ln \frac{2V\theta + S}{S} \tag{15}$$

For the turbulent case, equating (11) and (13) gives

$$\frac{4\pi JS_q c_p^3 (T_f - T_0)^3}{Q_f^2 N_f^2 N_0^2 \rho A^2 e \cdot -(2E/RT_f)} f(\sqrt{u^2}) = \frac{HS}{2V\theta} \ln \frac{2V\theta + S}{S}$$

or,

$$\frac{HSQ_f^2 N_f^2 N_0^2 \rho A^2 e \cdot -(2E/RT_f)}{8\pi V \theta S_q J c_p^3 (T_f - T_0)^3} \ln \frac{2V\theta + S}{S} = f(\sqrt{u^2}) \tag{16}$$

Equation (16) holds when the electrode spacing is less than quenching distance. When the electrode spacing is equal to or greater than the quenching distance, the equation is

$$\frac{HQ^2 N_f^2 N_0^2 \rho A^2 e^{-(2E/RT_f)}}{8\pi V\theta J_c^3 (T_f - T_0)^3} \ln \frac{2V\theta + S}{S} = f(\sqrt{u^2}) \quad (17)$$

#### APPLICATION OF THEORETICAL EQUATIONS TO EXPERIMENTAL DATA

##### Nonturbulent Flow

Only very limited data are available to verify the theoretical equations developed in this investigation. Data reported in references 1 and 2 were applied to equations (14) and (15) for nonturbulent flow. Although the turbulence was not determined, consideration of the apparatus used (refs. 1 and 2) indicates that the intensity of turbulence was probably low. In addition, several data points obtained in a more recent investigation (described in the appendix) were included. Since these data were obtained with one fuel, one fuel-air ratio, and one temperature, equation (14) becomes

$$\frac{S V\theta}{S_p H} = c_3 \ln \frac{2V\theta + S}{S} \quad (18)$$

and equation (15) becomes

$$\frac{V\theta}{pH} = c_3 \ln \frac{2V\theta + S}{S} \quad (19)$$

A plot of equations (18) and (19) is presented in figure 2. A mean curve has been drawn through the data points obtained with an electrode spacing equal to the quenching distance. The data points obtained with an electrode spacing less than the quenching distance, in general, fall slightly below this curve. This discrepancy is qualitatively expected, since a greater fraction of the spark energy originally present in the line source of ignition will be lost to the electrode when the electrode spacing is less than the quenching distance.

Further examination of the data of reference 1 shown in figure 2 reveals one important fact not specifically mentioned in the reference. Multiple sparks can be formed under certain conditions of velocity and spark duration as demonstrated in reference 6. For the data in question (ref. 1), reexamination of the oscillograms showed that multiple sparks occurred at all points which had values of  $(2V\theta + S)/S$  greater than approximately 10. Thus the correlation may not be valid for values of

$(2V\theta+S)/S$  greater than about 10, and therefore the correlation has not been applied to such data. An examination of two of five points having values greater than 10 showed that the energy and spark duration of the first of the series of multiple sparks could be determined with reasonable accuracy from original oscillograms. These values of energy and duration were applied to the correlation and found to agree with the plotted data. The new duration, of course, gave values of  $(2V\theta+S)/S$  less than 10.

Reference 1 also reports a small amount of fuel-air ratio data; attempts were made to apply equation (14) to these data. The results were inconclusive because of the scatter in the reference data, the lack of accurate quenching data, especially toward the lean and rich limits, and the severe quenching at the lean and rich limits.

The heated zone of the line source of ignition is moving at stream velocity and thus may be considered as a heated zone in a quiescent mixture. Hence, line-source ignition energies should be comparable to ignition energies of quiescent mixtures. Such comparison has been made in figure 3 using data from reference 4. Reasonable agreement is observed.

#### Turbulent Flow

The only data available to verify the turbulent-flow equation (15) are those contained in table I and described in the appendix. Since the data were obtained for one fuel, one fuel-air ratio, one temperature and one pressure, equation (17) reduces to

$$\frac{H}{V\theta} \ln \frac{2V\theta+S}{S} = f(\sqrt{u^2}) \quad (20)$$

Data calculated according to this relation are plotted in figure 4. Figure 4(a) was determined using the mean curves of the ignition-energy and turbulence data contained in the appendix, whereas figure 4(b) was determined using the actual data points. The figures show a reasonable relation between the energy required for ignition and the intensity of turbulence. The data (fig. 4(b)) correlated with an average deviation of 11 percent and a maximum deviation of 35 percent.

In development of the theory, the effect of scale of turbulence was considered unimportant. Experimental verification of this fact is indicated in table II, which shows a comparison of line-source energies at approximately constant intensities of turbulence but varying scales of turbulence. With the experimental errors involved and small variation in scale investigated, it must be concluded that the effect of scale is unimportant.

Kumagai and Kimura, of the University of Tokyo, have obtained data (presented at the third Japan Nat. Cong. for Appl. Mech., Tokyo, Sept. 9, 1953) which, to a certain extent, substantiate the theory presented herein. These data, which were obtained within the quenching distance, show that as the velocity is increased from zero, the energy for ignition with both long- and short-duration sparks first decreases and then increases. The velocity at which the energy starts to increase is about 6 feet per second, or approximately the lowest velocity considered in this report. The fact that the energy decreases as the velocity is increased from zero indicated that the line source of ignition moves away from the electrodes because of flow and thereby reduces the quenching effect of the electrodes. These data also show that the energy increases with increased turbulence.

#### CONCLUDING REMARKS

A theory of spark ignition in nonturbulent- and turbulent-flowing homogeneous gases using long-duration discharges has been developed, based on the concept that only a portion of the spark discharge length, a line source of ignition, is important in ignition. This theory resulted in a relation among ignition energy, gas density and velocity, electrode spacing, spark duration, intensity of turbulence, and fuel constants. The relation has been substantiated by a limited amount of data. The effects on the relation of other variables, such as fuel type and composition, have not been tested.

Lewis Flight Propulsion Laboratory  
National Advisory Committee for Aeronautics  
Cleveland, Ohio, July 1, 1954

## APPENDIX - EFFECT OF TURBULENCE ON ENERGY REQUIRED TO IGNITE

## PROPANE-AIR MIXTURE

Previously (ref. 3), an attempt was made to measure the effect of turbulence on spark-ignition energy. Analysis of the results obtained was limited, however, because, as revealed by hot-wire-anemometer measurements, pulsations and duct resonance were present that caused the turbulence spectrum to deviate from the characteristic spectrum. This deviation prevented analysis of data by usual means. The problem encountered not only with this equipment but also with jet-engine equipment is treated in reference 7, in which measurements and analysis of turbulent flow containing periodic flow fluctuations are described. In order to obtain more precise turbulence and ignition data to substantiate the theory presented in the report, the research of reference 3 was repeated. The apparatus described in reference 3 was modified to eliminate the flow fluctuations and to obtain a wider range of operating conditions. The results obtained are described in the following sections.

## Flow Apparatus

Two modifications were made to the apparatus described in reference 3. An additional flow-control valve  $V_3$  was added upstream of the orifice, and the test section length was increased. The modified apparatus is shown in figure 5. It was mentioned (ref. 7) that the pulsations and duct resonance that destroyed the characteristic turbulence spectrum were caused by the valves  $V_1$  and  $V_2$ . These valves were therefore opened fully and flow control was obtained by using valve  $V_3$ , whereupon a satisfactory spectrum was obtained. The length of the test section was increased so that a wider range of operating conditions could be investigated. This modification permitted the anemometer probes and electrodes to be installed at distances of 4, 8, 12, 16, and 20 inches from the turbulence promoter. Three turbulence promoters having mesh sizes 0.235, 0.525, and 0.625 inch and a mesh-to-diameter ratio of 5 were used. The ignition tests were conducted with a propane-air ratio of 0.0835 (by weight) at a chamber pressure of 5 inches of mercury absolute and a temperature of 80° F.

## Ignition System and Energy Measurement

The ignition and the energy-measuring systems are described in reference 2. The ignition system produced a single spark having a duration of approximately 500 microseconds and an exponential decay of current. Oscillographic techniques were utilized in the energy-measuring system. The electrodes used were shanks from number 74 high-speed drills (0.02250-in. diam.) and were located on the same center line perpendicular to the

direction of flow. The electrode spacing was maintained constant at 0.37 inch for most of the investigation. This spacing is the quenching distance for the particular pressure and fuel-air ratio used.

### Turbulence Measurement and Equipment

A description of the apparatus and methods used to measure the turbulence is included in reference 7. Single-wire probes measured the velocity fluctuations in the longitudinal direction and X-wire probes measured the velocity fluctuations in the lateral direction. The sensitive element of the probes was a tungsten wire 0.0002 inch in diameter and 0.10 inch in length with an unplated length of 0.080 inch. A difference circuit was used in the lateral measurements to obtain the difference in velocity fluctuations from the two wires of the X-wire probes. The spectrum of the turbulence was analyzed by means of a wave analyzer. An average-square computer totaled the kinetic energy in the velocity fluctuations to give the intensity of turbulence.

Measurements of the turbulence were made as follows: After the spark electrodes were removed, the probe was inserted into the test section and located so that the hot wire would be at the center of the duct. After air-flow conditions were set, the intensity of turbulence was determined from the average-square computer and a spectrum analysis was made, using the wave analyzer. Because of the length of time involved, only one spectrum was determined for each test point. The intensity data were corrected to compensate for the length of the hot wire by the method described in reference 8. The spectrum data were analyzed to determine the scale of turbulence.

### Turbulence Data

The data obtained from the turbulence measurements are presented in table I. The percent intensity of turbulence  $\sqrt{u^2}/V$  has been correlated with  $x/M$  as shown in figure 6; the usual form of the decay curve was obtained. The data correlated with some scatter; the average deviation from the mean curve was 12 percent and the maximum deviation 48 percent. The data show that the percent intensity decreases with distance  $x$  from the turbulence promoter and with decreasing mesh size  $M$ . The absolute intensity  $\sqrt{u^2}$  increases with velocity.

The mean curve of figure 6 is compared with similar curves obtained by other investigators in figure 7; the agreement is favorable. Figure 7 shows that data of the present investigation were obtained at values of  $x/M$  somewhat lower than those of other investigations, and these data may be partially in the nonisotropic region of turbulence. At large values of  $x/M$ , measurements of both longitudinal and lateral turbulence

showed that isotropic turbulence existed. At values of  $x/M$  less than 10, reproducibility and limited amount of data prevented good comparison of longitudinal and lateral measurements. The departure, if any, from isotropy was not great.

Scale measurements obtained are listed in table I. The method of measurement, described in reference 7, involves plotting of data on a grid and estimation of the scale from the resulting plot. Such a method was found to be subject to errors that might be as high as 25 percent.

### Ignition Data

The ignition-energy data obtained are listed in table I and plotted in figure 8. The data show that the ignition energy increases with increasing velocity, with increasing mesh size, and with decreasing distance between turbulence promoter and electrodes. The data were consistent except for the largest mesh size (0.625 in.) at  $x = 4$  inches. At this condition ignition was very erratic.

An examination of the data (table I) shows that the energy increases with those factors that give increased intensity of turbulence. Scale of turbulence appears to have minor effect as shown in table II in which an attempt has been made to compare ignition energies at constant intensity but variable scale.

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TABLE I. - TURBULENCE AND IGNITION-ENERGY DATA

[Pressure, 5.0 in. Hg abs.]

Mesh size, M, in.	Velocity, V, ft/sec	Distance downstream, x, in.	Intensity <sup>a</sup> of turbulence, $\sqrt{u^2}$ , ft/sec	Scale <sup>b</sup> of turbulence, L <sub>x</sub> , in.	Spark duration, $\theta$ , microsec	Ignition energy, <sup>c</sup> H, j
0.235	50	4	2.16	0.13	395	0.0113
		8	1.19	.20	381	.0106
		20	.638	.35	415	.0116
	100	4	2.49	0.20	346	0.0156
		8	1.88	.20	346	.0146
		20	.991	.30	325	.0137
	150	4	4.17	0.14	277	0.0197
		8	2.35	.19	277	.0184
		20	1.26	.20	311	.0157
	200	4	5.76	0.15	277	0.0264
		8	2.89	.20	277	.0217
		20	1.79	.30	249	.01827
0.525	50	4	3.44	0.17	464	0.0110
		12	1.28	.26	450	.0106
		20	.868	.30	415	.00955
	100	4	7.34	0.20	415	0.0212
		8	3.72	.23	381	.0165
		20	1.66	.30	388	.0141
	150	4	9.6	0.20	346	0.0295
		8	5.25	.20	346	.0195
		20	2.62	.27	332	.0158
	200	4	11.8	0.19	318	0.0464
		8	6.18	.20	346	.0252
		20	2.51	.30	318	.0230
0.625	50	4	4.0	----	415	0.0107
		8	2.03	----	415	.0114
		20	1.03	----	415	.0108
	100	4	7.04	----	346	0.0306
		8	3.61	----	346	.0149
		20	1.76	----	277	.00993
	150	4	9.08	----	311	0.0365
		8	5.68	----	277	.0209
		20	2.55	----	242	.0147
	200	4	11.8	----	346	-----
		8	6.92	----	277	0.0346
		20	3.35	----	208	.0232
No promoter	50	--	-----	----	346	0.00928
	100	--	-----	----	311	.0120
	150	--	-----	----	242	.0135
	200	--	-----	----	208	.0135

<sup>a</sup>Obtained using air.<sup>b</sup>Obtained using air. Data uncorrected for length of hot wire.<sup>c</sup>Fuel, propane; fuel-air ratio, 0.0835 (by weight); electrode spacing, 0.37 in.

TABLE II. - EFFECT OF SCALE OF TURBULENCE ON LINE SOURCE AND  
TOTAL IGNITION ENERGIES

Mesh size, M, in.	Distance, x, in.	Velocity, V, ft/sec	Intensity, $\sqrt{u^2}$ , ft/sec	Scale, $L_x$ , in.	Line-source energy, $H_S$ , j	Total ignition energy, H, j
0.235	8	50	1.19	0.17	0.0069	0.0106
.525	12		1.28	.26	.0066	.0106
0.235	4	200	5.76	0.15	0.0112	0.0264
.525	8		6.18	.20	.0096	.0252

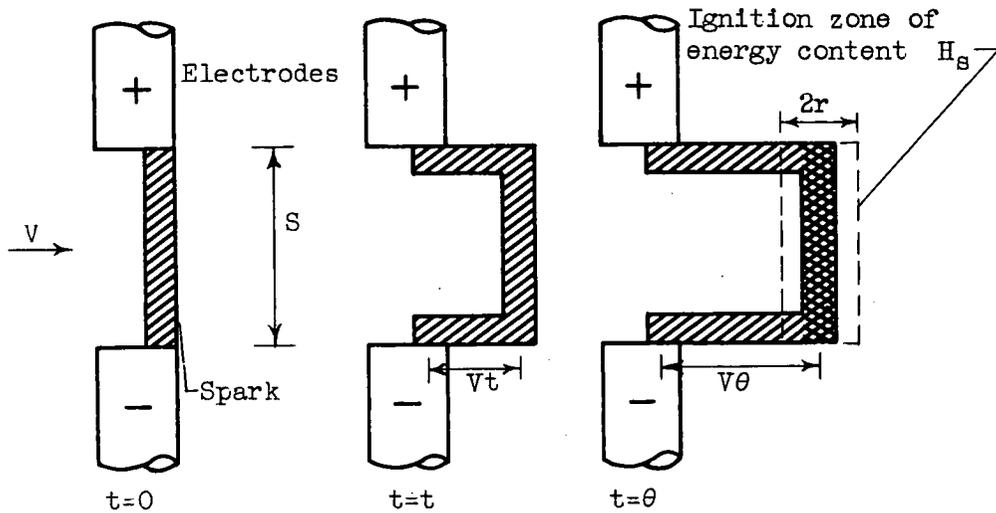


Figure 1. - Model of spark discharge in flowing gas.

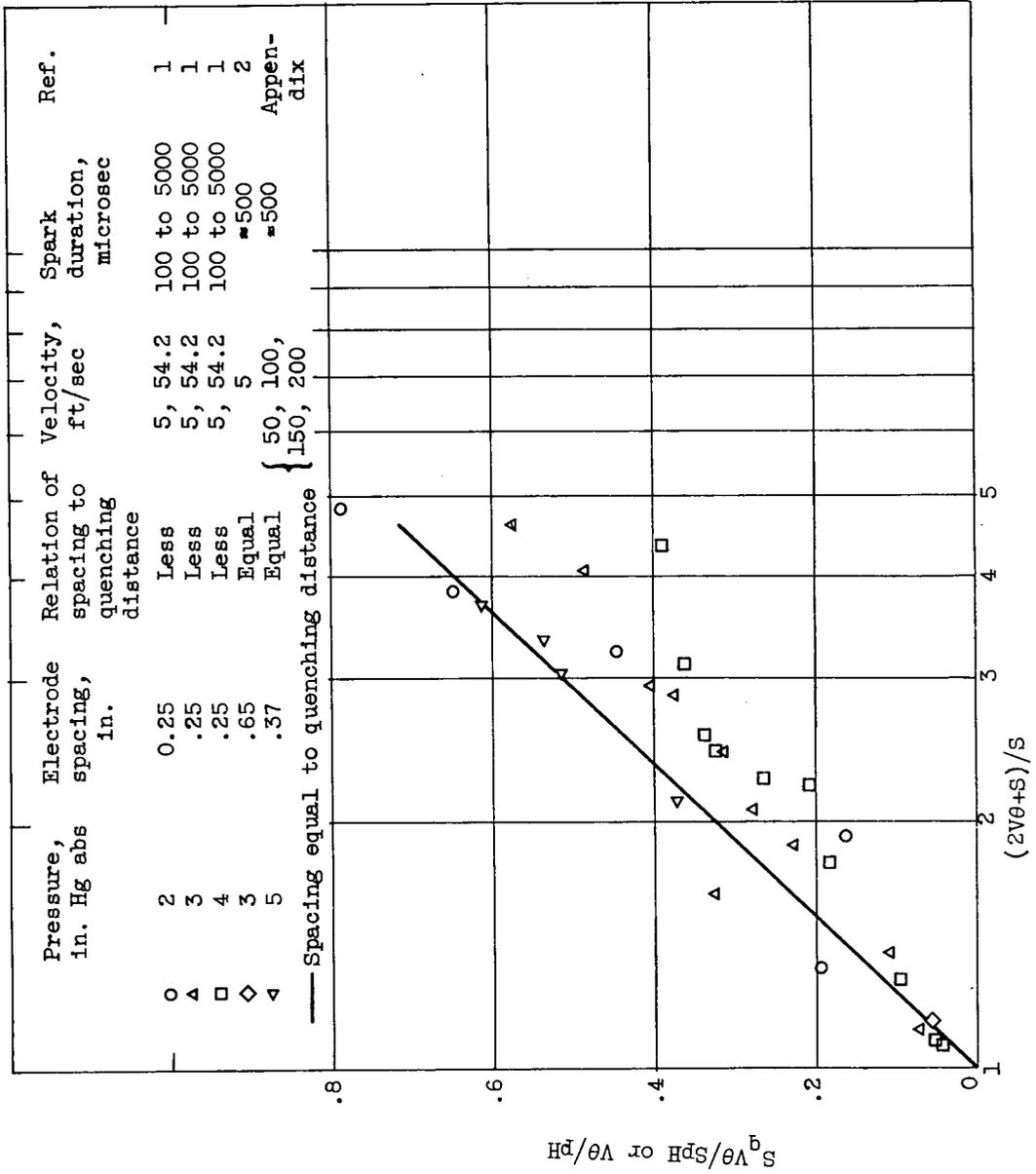


Figure 2. - Correlation of non-turbulent-flow ignition-energy data. Fuel, propane; fuel-air ratio, 0.0835.

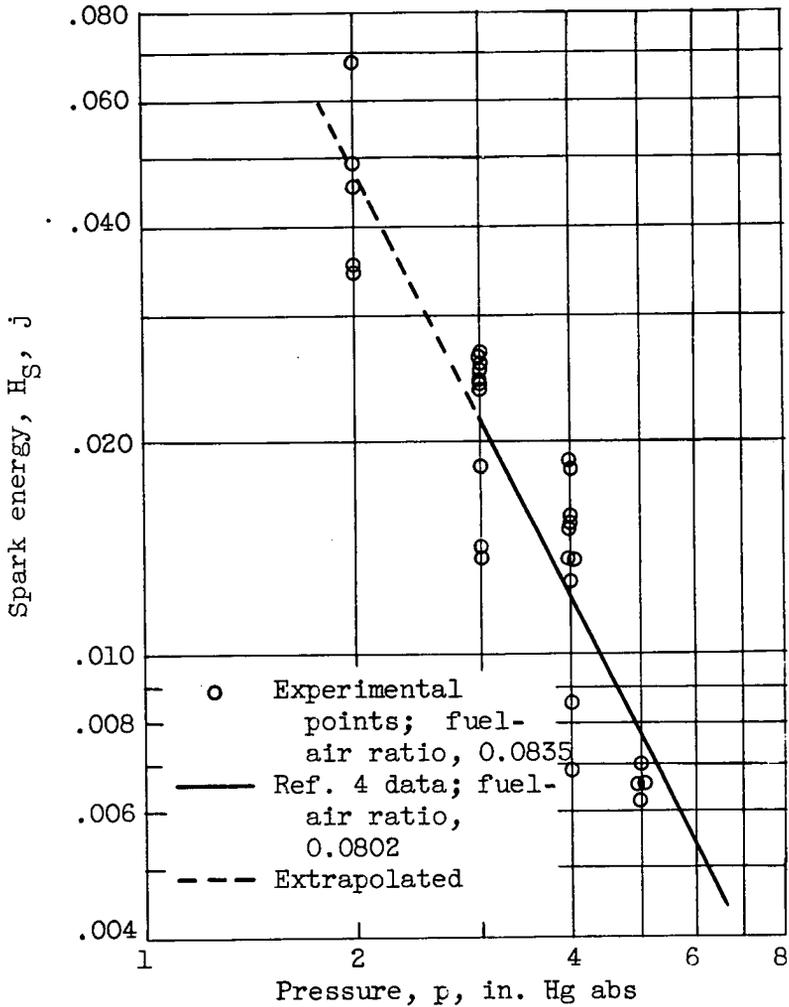
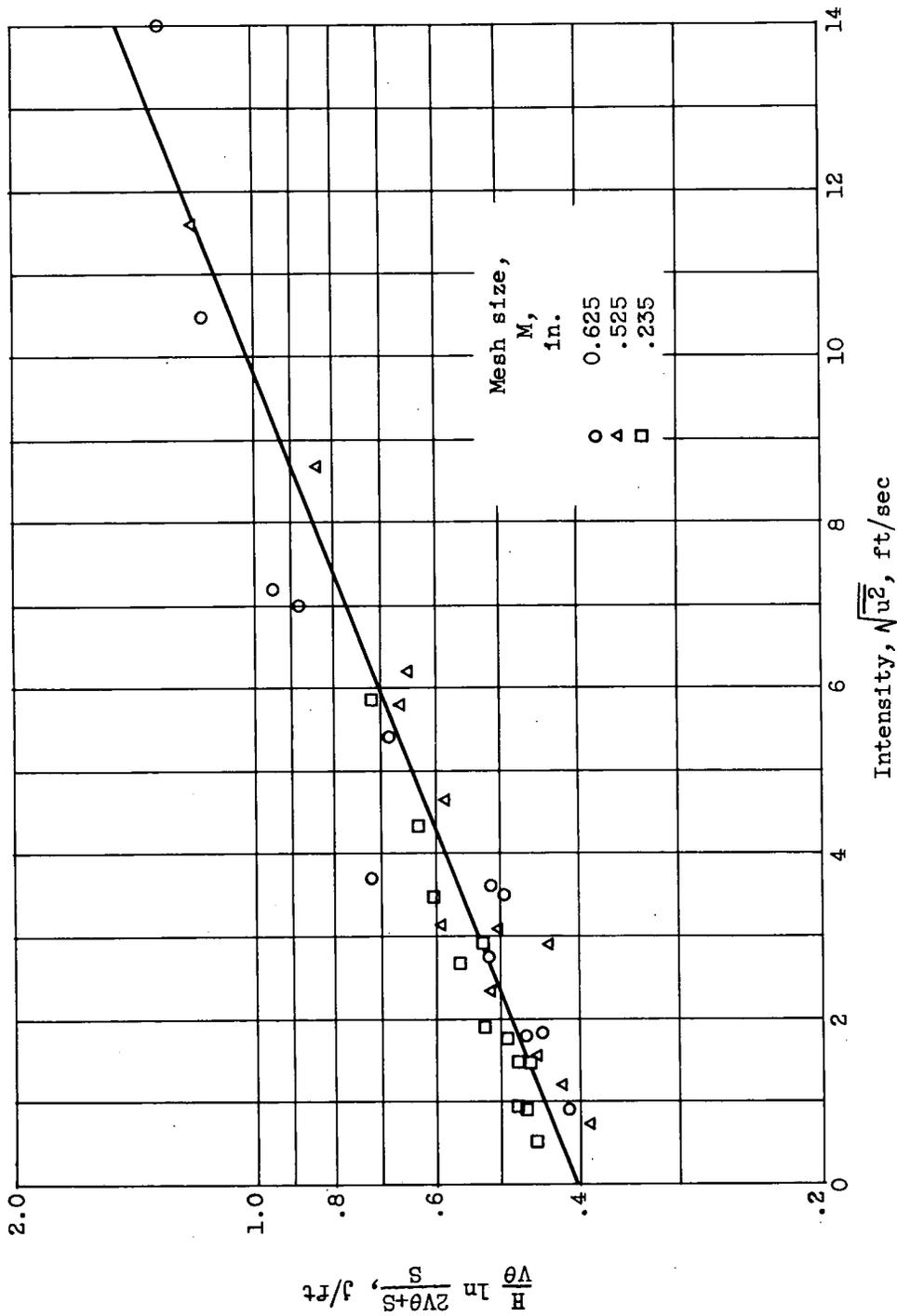
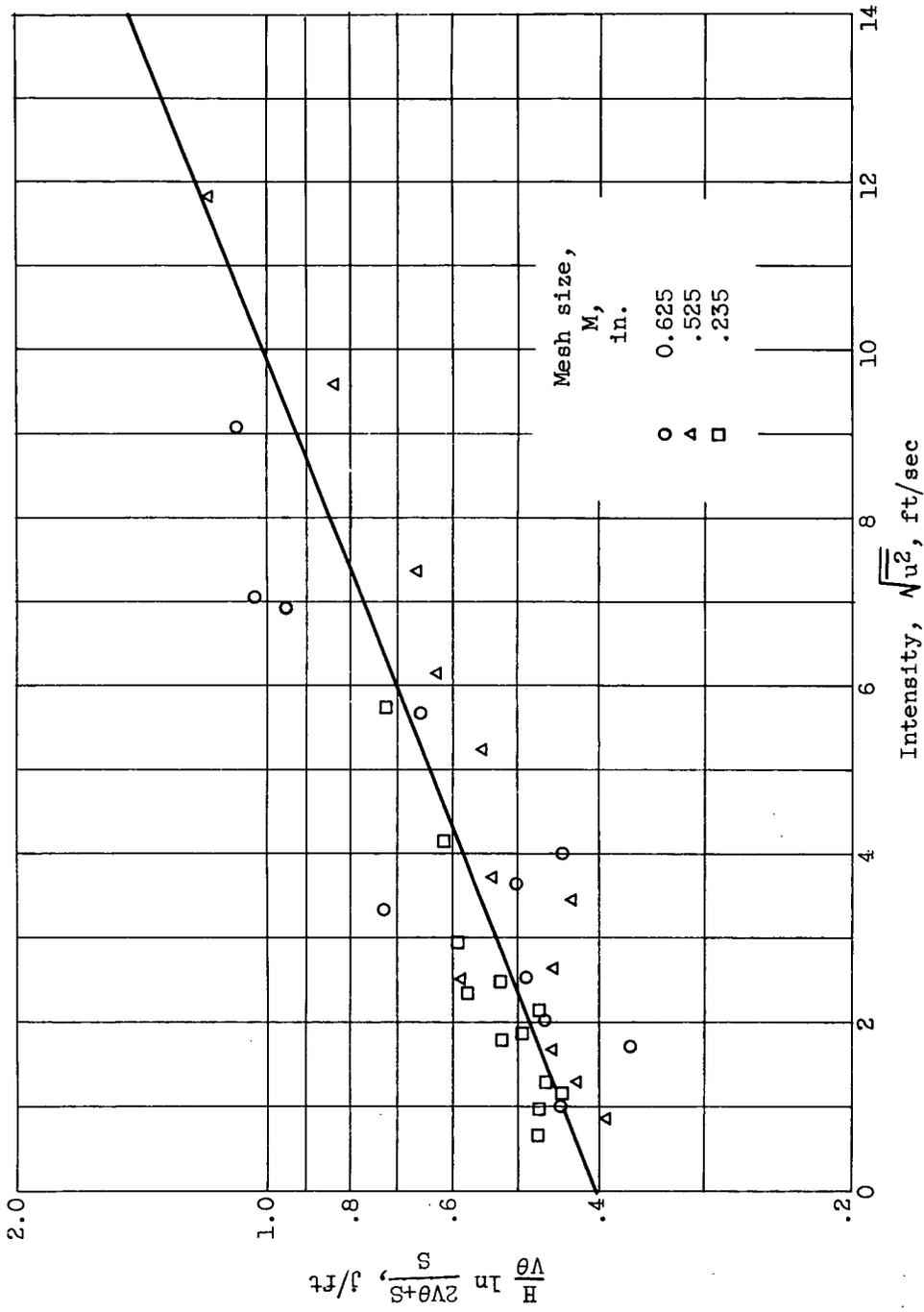


Figure 3. - Comparison of line-source energies with ignition energies of reference 4.



(a) From mean curves of ignition-energy and turbulence data.

Figure 4. - Correlation of ignition data with intensity of turbulence. Fuel-air ratio, 0.0835; temperature, 80° F; pressure, 5.0 inches of mercury absolute.



(b) Actual ignition-energy and turbulence data.

Figure 4. - Concluded. Correlation of ignition data with intensity of turbulence. Fuel-air ratio, 0.0835; temperature, 80° F; pressure, 5.0 inches of mercury absolute.

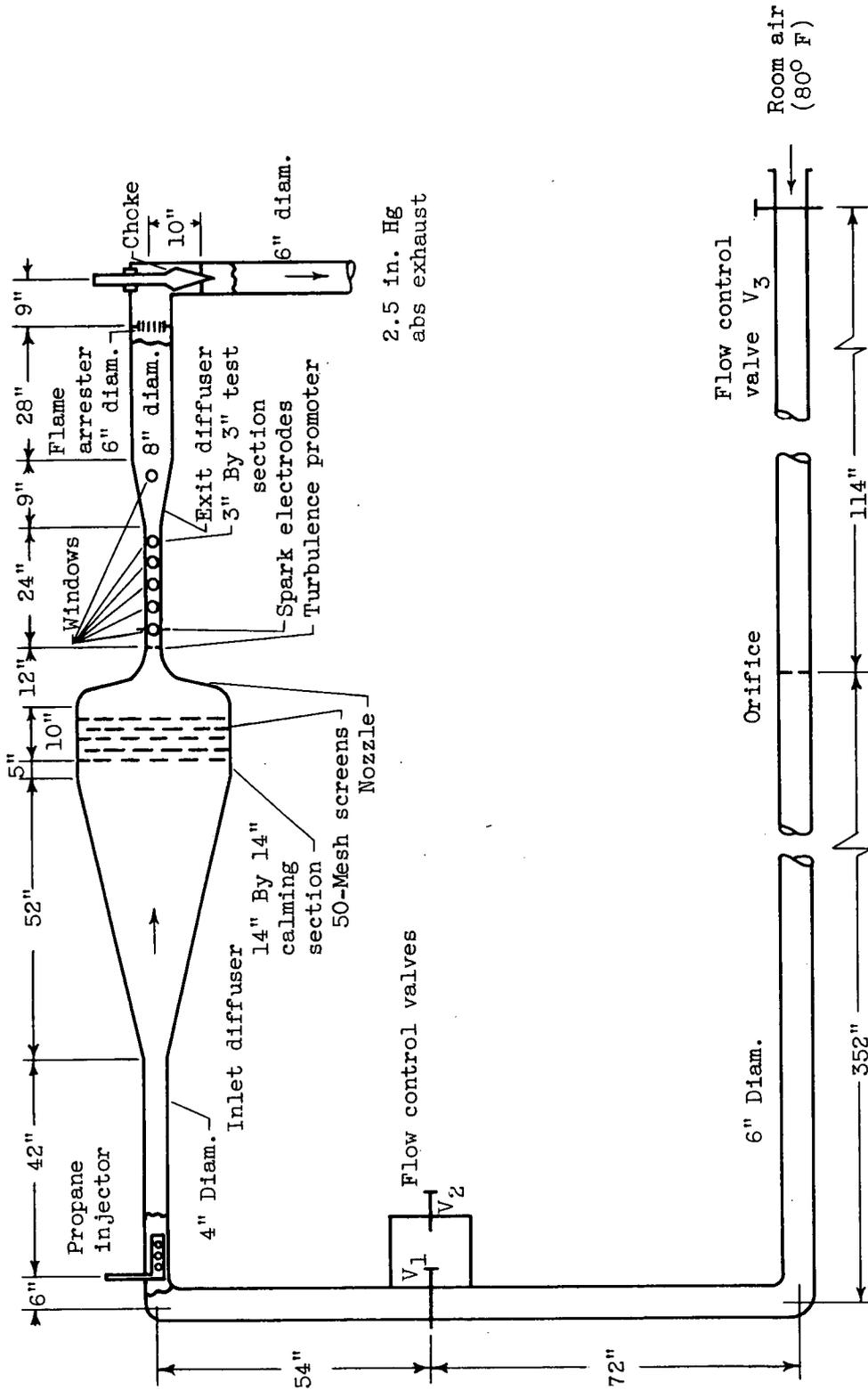


Figure 5. - Apparatus used for determining effect of turbulence on spark-ignition energy.

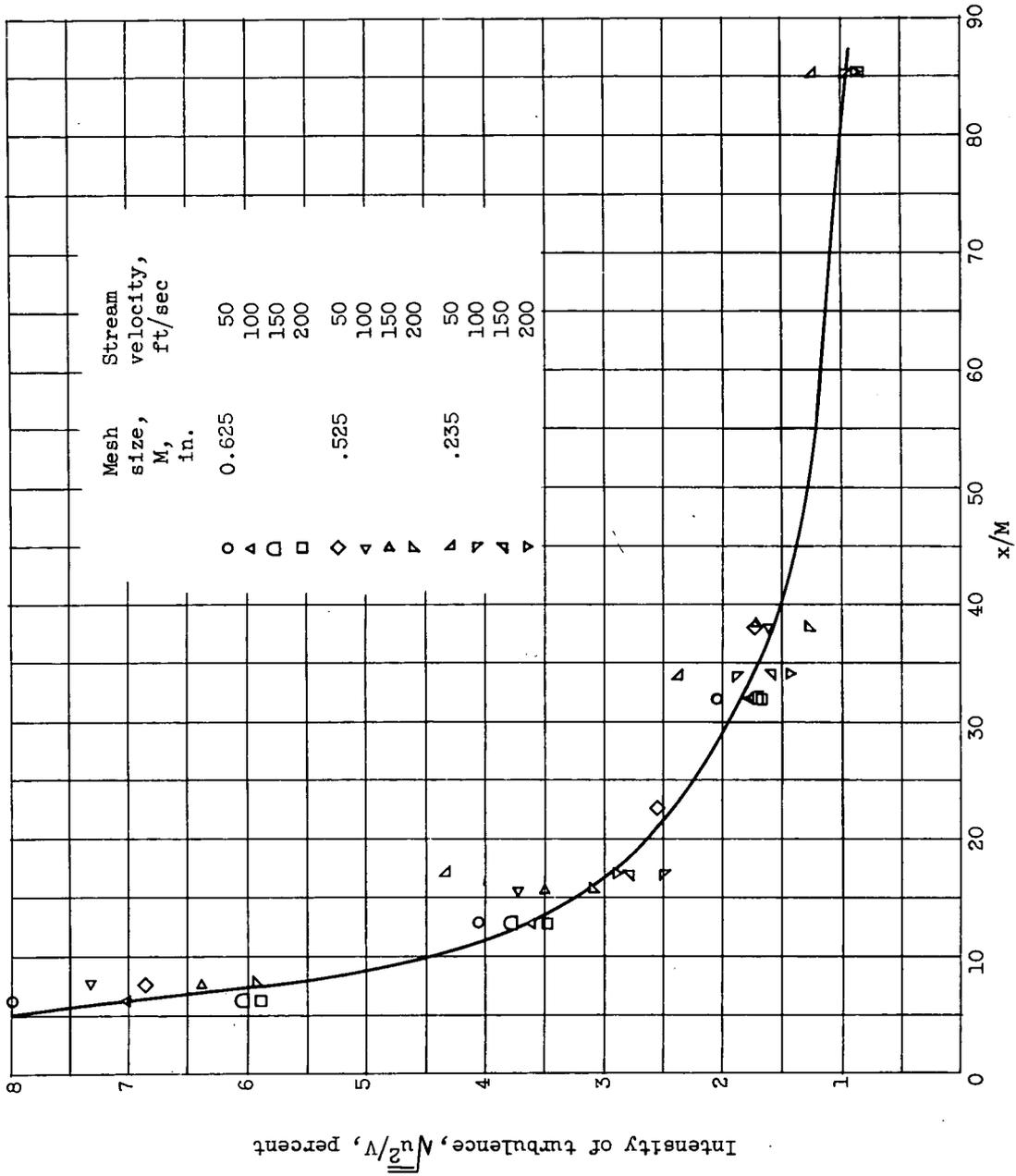


Figure 6. - Effect of  $x/M$  on  $\sqrt{u^2}/V$  for various values of mesh size and velocity.

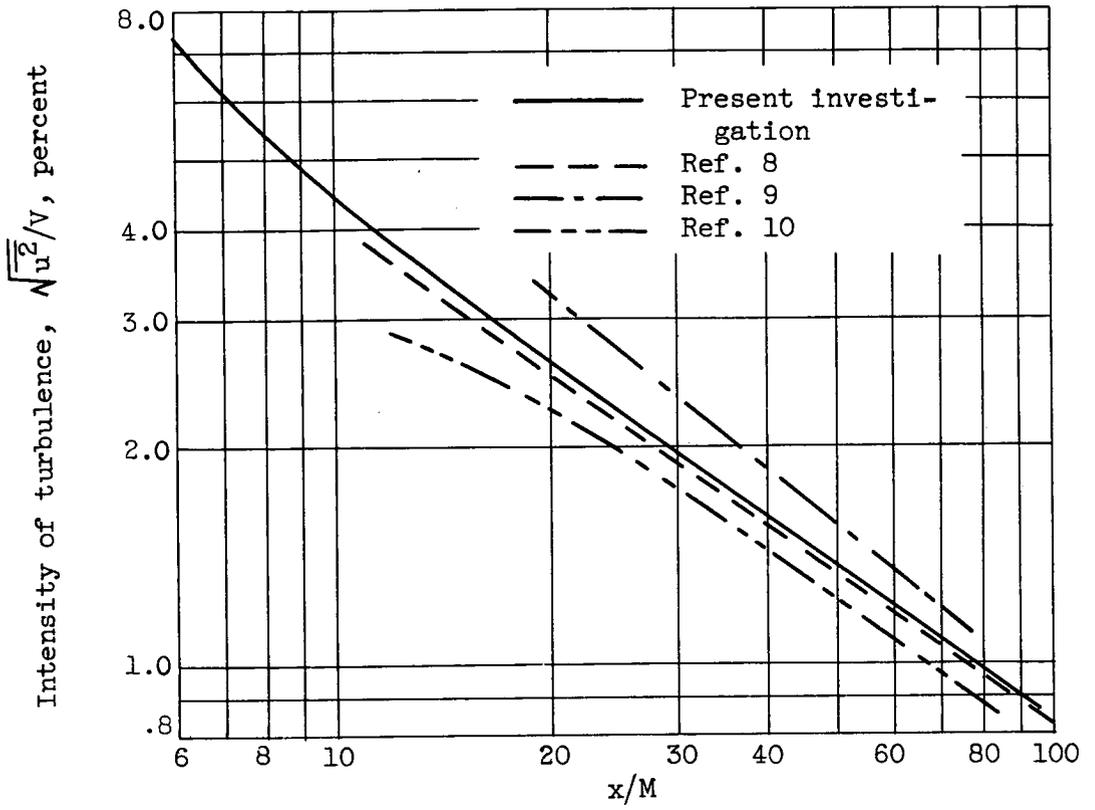
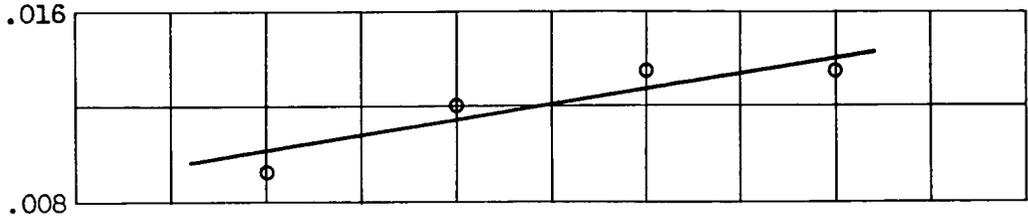
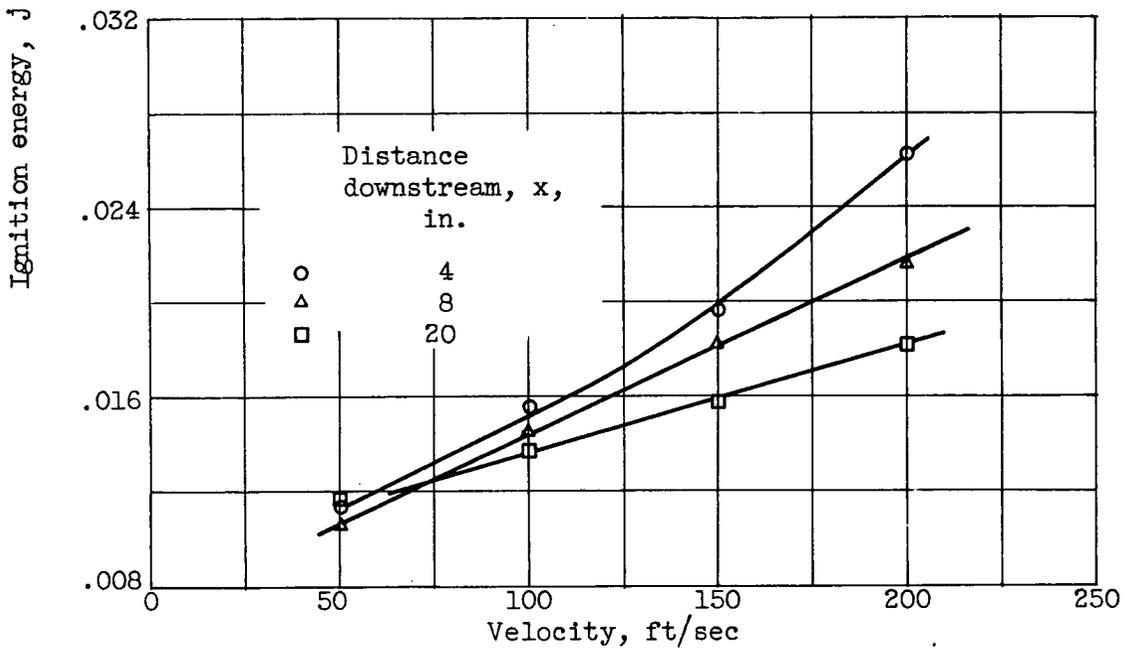


Figure 7. - Comparison of intensity data with that of other investigations.

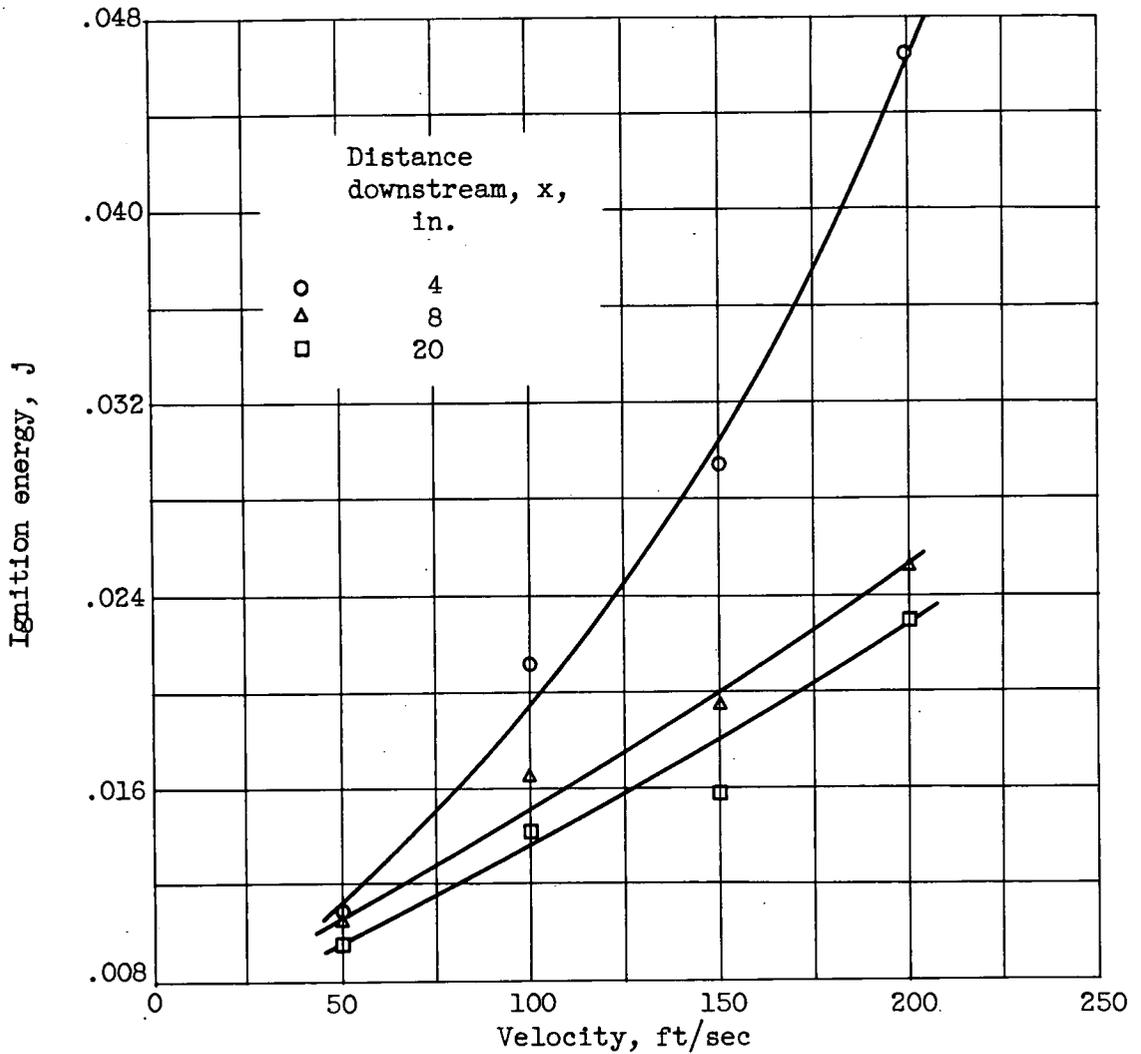


(a) No turbulence promoter.



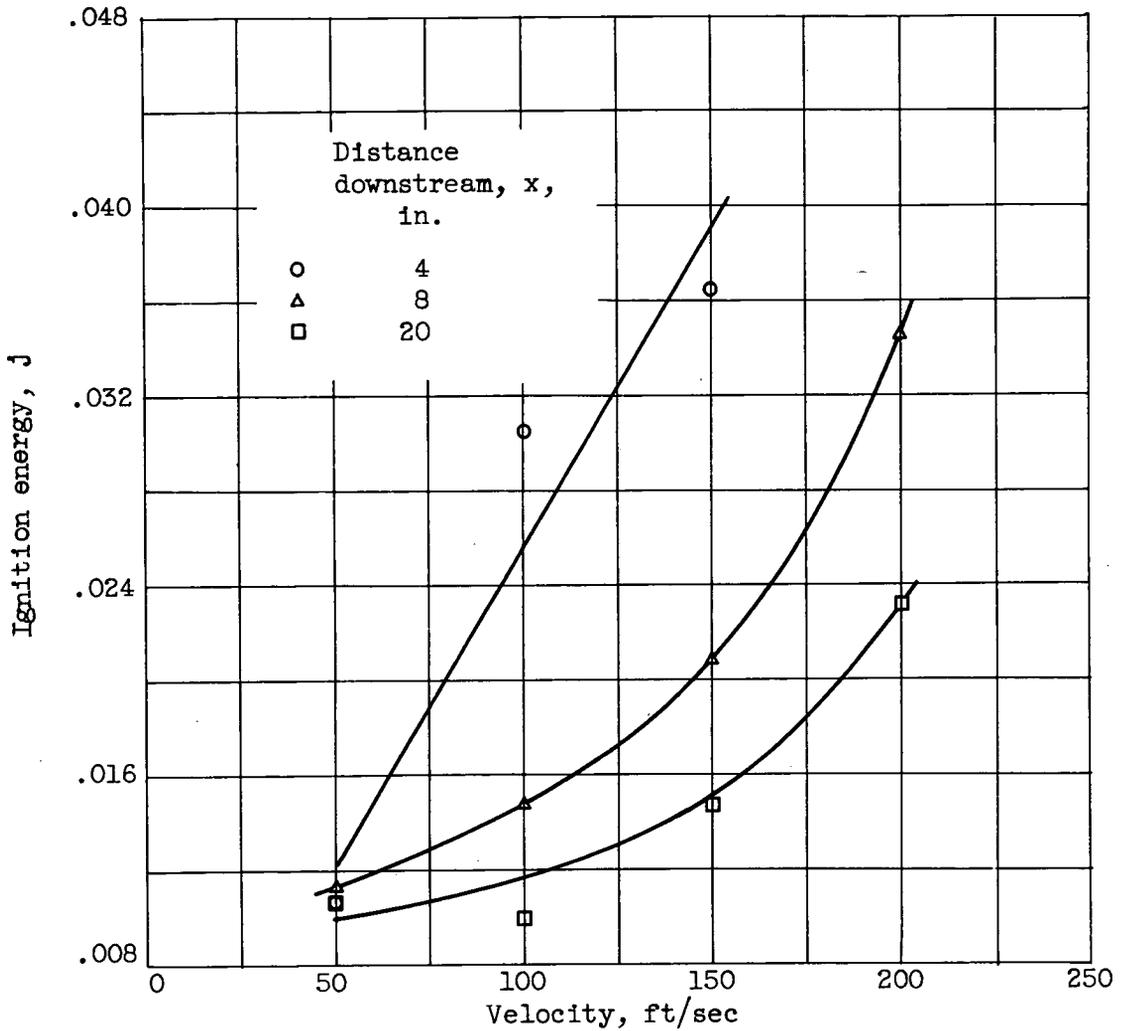
(b) Mesh size, 0.235 inch.

Figure 8. - Effect of velocity on ignition energy for various turbulence promoters. Fuel, propane; fuel-air ratio, 0.0835; pressure, 5.0 inches of mercury absolute; spacing, 0.37 inch; spark duration, approximately 500 microseconds.



(c) Mesh size, 0.525 inch.

Figure 8. - Continued. Effect of velocity on ignition energy for various turbulence promoters. Fuel, propane; fuel-air ratio, 0.0835; pressure, 5.0 inches of mercury absolute; spacing, 0.37 inch; spark duration, approximately 500 microseconds.



(d) Mesh size, 0.625 inch.

Figure 8. - Concluded. Effect of velocity on ignition energy for various turbulence promoters. Fuel, propane; fuel-air ratio, 0.0835; pressure, 5.0 inches of mercury absolute; spacing, 0.37 inch; spark duration, approximately 500 micro-seconds.