THE INFLUENCE OF FLOW PARAMETERS ON MINIMUM IGNITION ENERGY AND QUENCHING DISTANCE

by

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SUMMARY

Experiments have been carried out on the effects of pressure, velocity, mixture strength, turbulence intensity and turbulence scale on minimum ignition energy and quenching distance. Tests were conducted at room temperature in a specially designed closed-circuit tunnel in which a fan was used to drive propane/air mixtures at subatmospheric pressures through a 9 cm square working section at velocities up to 50 m/s. Perforated plates located at the upstream end of the working section provided near-isotropic turbulence in the ignition zone ranging from 1 to 22 percent in intensity, with values of turbulence scale up to 0.8 cm. Ignition was effected using capacitance sparks whose energy and duration could be varied independently.

The results of these tests indicated an optimum spark duration for minimum ignition energy of 60 μsec. Rectangular, arc-type sparks of this duration gave lower than previously reported values of ignition energy for both stagnant and flowing mixtures. It was found that both quenching distance and minimum ignition energy increase with (a) increase in velocity, (b) reduction in pressure, (c) departures from stoichiometric fuel/air ratio, and (d) increase in turbulence intensity. Increase in turbulence scale either raised or lowered ignition energy, depending on the level of turbulence intensity. Equations based on an idealized model of the ignition process satisfactorily predicted all the experimental data on minimum ignition energy.

INTRODUCTION

Although the process of ignition has been subjected to many experimental investigations, the amount of published data on spark ignition in turbulent, flowing gases is relatively small. In fact, the only major contribution in this area is that of Swett[1] who studied the effects on ignition energy of variations in pressure, velocity, fuel/air ratio and turbulence. Experience on many types of combustion system have generally confirmed the trends observed by Swett. Nevertheless, his experimental values are considered suspect for the following reasons:

1 In some experiments the spark gap width was below the quenching distance, thereby incurring excessive heat loss to the electrodes.[2]

2 No independent control was exercised over certain important spark characteristics. For example, spark duration varied with flow velocity and often exceeded the optimum value.[3]

3 A glow discharge was employed instead of the more efficient arc discharge.[1]

4 The treatment of turbulence was very limited; for example, no consideration was given to the effects of turbulence scale.

In view of these deficiencies, and bearing in mind the importance of accurate experimental data to the design of ignition equipment and the development of ignition theory, it was decided to undertake a detailed and systematic investigation of the main parameters influencing minimum ignition energy and quenching distance in flowing mixtures, namely, pressure, velocity, fuel/air ratio, turbulence intensity and turbulence scale.

EXPERIMENTAL

Tests were carried out at room temperature in a specially designed closed-circuit tunnel in which a fan is used to drive air through a 9 cm square working section at velocities up to 50 m/s. As this system is totally enclosed it is ideally suited to the study of ignition in flowing gaseous mixtures at subatmospheric pressures. Located at the upstream end of the working section are various perforated plates which can generate near-isotropic turbulence in the ignition zone ranging from 1.0 to 22 percent in intensity, with values of turbulence scale up to 0.8 cm. The working section, as illustrated in Fig.1, is fitted on two opposing walls with schlieren-free glass windows to allow the initiation and development of the spark kernel to be visually observed and photographed.

The turbulence properties of the flow were examined in detail at a pressure of 0.17 atmospheres. At such low pressures Knudsen number effects on the heat transfer from conventional hot wires of 2 - 5 μm diameter become significant. To overcome this problem a 70 μm diameter hot wire was chosen, based on the criterion of Boltz.[4] This has an upper frequency response of 30 KHz which was considered adequate. Further details of the lengthy calibration procedures employed are contained in Ref.5.

The signals from the hot wire were processed using a Disa 55D01 Universal anemometer, a Disa 55D10 linearizer and a B & K type 2107 frequency analyzer. Turbulence intensity was read directly off an RMS voltmeter. Measurements were made of both large scale, L, and Taylor microscale, λ. The Kolmogoroff scale, η, was then computed since it is useful for calculating the dissipative effects of turbulence and also facilitates examination of the role of turbulent vorticity in combustion. Moreover, the combination of L, λ and η provides a fairly complete description of the turbulent energy spectrum.[6]

Details of the perforated plates employed to generate turbulence are contained in the Appendix. From measurements carried out with an X probe, it was found that the turbulence was nearly isotropic ($u' \approx 0.9\ v'$ for $u'/U < 5$ percent, $u' \approx 0.75$ to $0.8\ v'$ for high values of u'/U). At all conditions the Reynolds number of turbulence, Re_λ, was sufficiently high for the turbulent flow in the ignition zone to be in the 'initial period' of its decay.

Although many different electrode geometries and materials were investigated, plain electrodes were selected because of their relatively large area of contact with the gas which allowed accurate definition of quenching distance. Heat resistant stainless steel was considered to be the most suitable electrode material due to its low thermal conductivity and high wear resistance. The choice of electrode diameter posed problems since it was recognized that too large a size would alter the intensity and scale of the turbulence in the flame propagation zone, while too small a size would prohibit accurate definition of quenching distance. An electrode diameter of 1 mm was eventually decided upon as being slightly smaller than the lowest measured value of λ. Accurate control of the gap width was accomplished using a micrometer head attached to one electrode.

Spark energies were measured by mounting high voltage Tektronix P6015 probes (supplied with compensating networks) on the electrodes and feeding their output into a two-channel oscilloscope. Traces of current and voltage were recorded on a polaroid film and the spark energy obtained as the integral of current and voltage readings. In all experiments a minimum current density of 50 amps/cm^2 was maintained in the electrodes in order to prevent the possible occurrence of a glow-type discharge.[7] The electrodes were connected to an ignition unit designed to supply 'rectangular' shaped sparks whose energy and duration could be varied independently. This type of spark was chosen on the basis of a recent separate study carried out by the authors to determine optimum spark characteristics for minimum ignition energy.[3]

Before each test the tunnel was evacuated and then supplied with air and propane to the desired pressure and fuel/air ratio. The fan was then started and its speed adjusted to give the required velocity through the working section. The ignition unit was then switched on and the spark energy gradually increased until the onset of ignition. The criterion for a successful ignition was the visual appearance of flame. After each run the system was purged in preparation for the next test.

This procedure was carried out at each operating condition for several different values of gap width. By plotting a graph of ignition energy against gap width, E_{min} was obtained as the lowest point on the graph, while quenching distance was defined as the gap width corresponding to E_{min}. The experimental data were tested for repeatability by making 25 separate measurements of E_{min} at a number of different operating conditions. At any one condition the maximum scatter obtained was less than 7 percent. This was considered satisfactory. Some of the results obtained on d_q and E_{min} for a near-stoichiometric propane/air mixture at a pressure of 0.17 atmos are listed in Table 1 along with corresponding measured values of u', L, λ and η. These data were all obtained using a spark duration of 60 μs, since a preliminary series of tests had shown this to be the optimum duration for minimum ignition energy. Some of the results of these tests are presented in Fig.2. In all subsequent experiments a constant spark duration of 60 μs was employed.

RESULTS

Mixture strength

Figures 3 and 4 respectively show the influence of mixture strength on E_{min} and d_q. It is of interest to observe that these and other curves exhibit minimum values at an equivalence ratio of around 1.04, which corresponds to maximum flame temperature for propane/air mixtures at this pressure. This tends to suggest that thermal processes are controlling, which is at variance with the selective diffusion mechanism proposed by Swett[1] and Lewis and von Elbe[2] to account for their observed shift in E_{min} and d_q values towards much richer mixture strengths. With flowing mixtures, however, it seems probable that transport processes within the flame zone are accelerated to an extent which outweighs the effects of preferential diffusion rates. In the present work it was observed that as velocity increased from 0 to 20 m/s, the value of Ø corresponding to minimum ignition energy decreased from 1.1 to 1.04. Moreover, a careful study of all published work on spherically or cylindrically expanding flames revealed that maximum values of turbulent flame speed always occurred at Ø = 1.04 (see, for example, Fig.25, Ref.8 and Fig.5, Ref.9).

Thus for turbulent flowing mixtures it would appear that both quenching distance and ignition energy attain minimum values at mixture strengths corresponding to maximum flame temperature. However, to clarify this point, further tests are planned using higher hydrocarbon fuels, e.g. hexane, for which the reported difference between the equivalence ratios corresponding to (a) maximum flame temperature and (b) minimum ignition energy (stagnant mixtures) is much greater than for propane.

Velocity

The adverse effect on E_{min} of an increase in flow velocity is illustrated in Fig.5. This occurs mainly because the spark kernel, during the initial period of its development, becomes more diluted with cold mixture, thus requiring more energy to compensate for the loss of heat. However, velocity also tends to displace the spark in a downstream direction, thereby reducing the loss of heat and active radicals to the electrodes. This effect is especially significant for an arc discharge where most of the energy lies in a positive column which is distributed fairly symmetrically between the electrodes. However, with a glow discharge most of the energy, typically about 60 percent, is concentrated in the vicinity of the cathode. Therefore the shifting of the positive column away from the quenching action of the electrodes is much more beneficial for an arc discharge than for a glow discharge. This could explain why the E_{min} values obtained in the present study show a lower dependence on velocity than the measurements of Swett.[1]

Pressure

The effects of pressure on quenching distance and minimum ignition energy are shown in Figs. 6 and 7 respectively for various values of equivalence ratio. Analysis of these and other data obtained at different velocities indicates that $d_q \propto P^{-0.93}$, which is consistent with previously reported data on stagnant mixtures and implies a second order reaction.[10]

The pressure exponents obtained for E_{min} at various values of equivalence ratio are shown in Fig.8. In general, the effect of variation in equivalence ratio on n follows the same trends reported for stagnant mixtures except that all values are lower. Fig.8 also shows that while n = 2 for stagnant mixtures, the effect of velocity is to rapidly reduce n to a value of 1.25 when fully developed flow is attained, beyond which the pressure exponent slowly declines with further increase in velocity. The theoretical implications of this result are discussed below.

Turbulence intensity

Turbulence affects the ignition process in several different ways. First, it promotes ignition by wrinkling and lacerating the flame front, thereby effectively increasing its surface area for propagation. Moreover, within the flame zone itself the transport of radicals and other active species is accelerated. However, at the same time turbulence increases the loss of heat by diffusion to the surrounding unburned gas. The experimental evidence obtained, as illustrated in Figs. 9 and 10, shows that the latter effect is overriding and that both quenching distance and ignition energy increase with increase in turbulence intensity.

Turbulence scale

In previous studies of ignition no effect of turbulence scale on ignition energy was observed, either because scale was not varied over a sufficiently wide range or because any change in scale was accompanied by a simultaneous change in some other important flow parameter. In the present study, a number of experiments were specially designed in which wide variations in turbulence scale were created within the ignition zone, at constant values of mainstream velocity and turbulence intensity. In this way it was possible to study the separate effects on ignition energy of turbulence intensity and turbulence scale.

The results obtained on turbulence scale for stoichiometric mixtures are presented in Fig.11. This figure shows that at low values of u'/S_L, E_{min} decreases with increase in scale. However, as u'/S_L is raised, the dependence of E_{min} on L changes in a complicated manner which is illustrated more clearly in Fig.12. This shows for both L and η the rate of change of minimum ignition energy with scale as a function of turbulence intensity. This figure demonstrates the existence of transition regions at $u' \approx S_L$ and $u' \approx 4S_L$. Between these values E_{min} increases with increase in scale; however, at lower and higher values of u', E_{min} diminishes with increase in scale. It is of interest to note that analysis of data on turbulent burning velocities[11] reveals a transition region around $u' \approx 2S_L$ corresponding to the peak value of $d\,E_{min}/dL$ in Fig.12. It is clear therefore that any proposed ignition theory must take into account the important effects of turbulence scale.

THEORY

The process of spark ignition in a flowing combustible mixture is visualized as follows:- initial passage of the spark creates a cylindrical volume of hot gas between the electrodes.

As the spark discharge proceeds the effect of the flow is to extend this volume in a downstream direction, as illustrated in Fig.13. Under favourable conditions, the rate of heat generation by chemical reaction at the kernel surface may exceed the rate of heat loss by turbulent diffusion. If this happens the spark kernel will continue to expand and a successful ignition is assured. However, if for any reason the rate of heat release at the kernel surface is less than the rate of heat loss, the temperature within the kernel will continue to fall until the reactions cease altogether. Thus, as in previous theories,[1,2,12,13] of critical importance is the size to which the spark kernel has grown by the time its temperature has fallen to the normal flame temperature of the mixture. The criterion for successful ignition is that at this point the rate of heat release in the reaction zone surrounding the spark kernel should exceed the rate of heat loss from the volume. This model for the ignition process is similar to that employed by Swett,[1] the essential difference being that whereas Swett's theory contemplates heat generation throughout the entire spark volume, the present theory is based on the assumption that the heat release occurs entirely in the flame front itself. ~~This approach is believed to be more realistic because it is difficult to conceive how heat generated at the centre of the kernel can compensate for heat loss at the boundary.~~

In the proposed model for ignition the above criterion is satisfied when the width of the spark kernel is just equal to twice the thickness of the flame zone, i.e. $d_c = 2\delta_L$ or $2\delta_T$ as shown in Fig.13. On this basis it is possible to derive equations for d_c for each region of turbulent flow. This has been done and the results may be summarized as follows:-

$$U = 0 \qquad d_c = 2\delta_L = 2k/c_p.\rho.S_L \tag{1}$$

$$u'/S_L \approx 0 \qquad d_c = \frac{2k}{c_p.\rho.S_L}\left[1 + 0.45.Re_{\delta_L}\right] \tag{2}$$

$$u'/S_L < 1.5 \qquad d_c = \frac{2k}{c_p.\rho.S_T}\left[1 + 14\left(Re_L\right)\left(u'/S_L\right)^{0.5}\right] \tag{3}$$

$$u'/S_L \approx 2 \qquad d_c = \frac{2k}{c_p.\rho.S_T}\left[1 + 7\left(Re_L\right)\left(u'/S_L\right)^{0.5}\right] \tag{4}$$

$$u'/S_L > 3 \qquad d_c = \frac{2k}{c_p.\rho.S_T}\left[1 + 400\left(u'.\delta_L/S_L.L\right)^{0.75}\left(u'/S_L\right)^{.375}\right] \tag{5}$$

In Eq.(2) the term Re_{δ_L} represents the additional loss of heat from the spark kernel due to the effect of mainstream velocity under conditions of very low turbulence. In Eqs.(3) and (4) the terms Re_L and (u'/S_L) may be regarded as representing respectively the additional heat loss arising from (a) wrinkling of the flame front, and (b) increased "roughness" of the flame surface. The only basic difference between Eq.(5) and Eqs.(3) and (4) is that L now appears in the denominator. This is consistent with the results of the authors' work on the effects of turbulence on burning velocity.[11] These showed that, under conditions of low turbulence intensity, increase in L raises S_T, presumably due to increased wrinkling of the flame front. However, when the turbulence intensity is high, increase in L tends to stretch the flame surface (via the term $u'.\delta_L/S_L.L$ in Eq.5) thereby reducing its roughness.

In Eqs.(2 to 5) the constants 0.45, 14, 7 and 400 were chosen to give a best fit to the experimental data. Minimum ignition energies were calculated by inserting appropriate values of d_q and d_c, from Eqs.(1 to 5), into the following expression for E_{min}:

$$E_{min} = J.c_p.\rho.\Delta T.V. \qquad (6)$$

where V = kernel volume = $d_q\left(\pi/4.d_c^2 + U.t_s.d_c\right)$

The results of calculations of E_{min} for a range of values of pressure, velocity, mixture strength, turbulence intensity and turbulence scale are plotted in Fig.14 against actual measured values. In all calculations the values of S_T employed were obtained from the experimental data and dimensionless equations for S_T/S_L presented in Refs.(14) and (11). The level of agreement shown is considered very satisfactory.

CONCLUSIONS

1 Experimental studies on the spark ignition of propane/air mixtures using 'rectangular' arc discharges of optimum duration have demonstrated significantly lower than previously reported values of ignition energy for both stagnant and flowing mixtures.

2 Earlier findings on the adverse effect of mainstream velocity on ignition are confirmed. It is suggested that the main effect of velocity is in promoting heat loss from the spark kernel during the passage of the spark. Upon completion of the spark the kernel is rapidly accelerated to the mainstream velocity and from then on is subject only to the fluctuating components of velocity.

3 For flowing gases ignition energies are lowest at mixture strengths corresponding to maximum flame temperature.

4 Ignition energies increase with reduction in pressure according to relationship $E_{min} \propto P^{-n}$. For stagnant stoichiometric mixtures n = 2 but, with the onset of flow, n falls rapidly, reaching a value of 1.25 when fully developed flow is attained. Any departure from $\phi = 1$ towards either richer or leaner mixtures causes further reduction in the value of n.

5 Increase in turbulence intensity raises E_{min}.

6 E_{min} may increase or decrease with increase in turbulence scale depending on the level of turbulence intensity. Transition regions are observed around $u' \approx S_L$ and $u' \approx 4S_L$ in which E_{min} is sensibly independent of turbulence scale.

7 Experimental data on quenching distance follow the same general trends as for minimum ignition energy. Thus it is found that quenching distance increases with increases in velocity and turbulence intensity, and with reduction in pressure.

8 Equations based on an idealized model of the ignition process, in conjunction with previously derived expressions for turbulent burning velocity, satisfactorily predict all the experimental data obtained on E_{min}, including the effects of turbulence intensity and scale, and also the reduction in pressure exponent with increase in velocity.

NOMENCLATURE

S_L	=	laminar burning velocity, cm/s.
S_T	=	turbulent burning velocity, cm/s.
U	=	mainstream velocity, m/s or cm/s.
u'	=	r.m.s. value of fluctuating velocity, cm/s.
L	=	Integral scale of turbulence in transverse direction, cm.
λ	=	Taylor microscale of turbulence, cm.
η	=	Kolmogoroff scale of turbulence, cm.
k	=	thermal conductivity, cal./cm.s. ^{o}C.
ν	=	kinematic viscosity, cm^2/s.
c_p	=	specific heat, cal./gm. ^{o}C.
ρ	=	density, gm/cc.
ΔT	=	temperature rise due to combustion, ^{o}C.
E_{min}	=	minimum ignition energy, mJ.
δ_L	=	laminar flame thickness, cm.
δ_T	=	turbulent flame thickness, cm.
d	=	thickness of spark kernel, cm.
d_c	=	critical thickness of spark kernel, cm.
d_q	=	quenching distance, cm.
V	=	spark kernel volume, cc.
ϕ	=	equivalence ratio.
Re_{δ_L}	=	$(U.\delta_L/\nu)$
Re_L	=	$(u'L/\nu)$
Re_λ	=	$(u'\lambda/\nu)$
P	=	pressure.
n	=	pressure exponent.
t_s	=	spark duration.
J	=	conversion factor, calories to millijoules. (J = 4,187)

APPENDIX

Specifications of perforated plates

Grid No	hole dia., cm	Pitch, cm
1	0.400	0.532
2	0.231	0.355
3	1.110	1.250
4	1.110	1.358
5	1.110	1.460
6	1.110	1.562
7	0.668	1.270
Plate thickness = 0.30 cm		

A 40 mesh grid was used to smoothen the natural pipe turbulence to an intensity of less than 1 percent.

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TABLE 1

S_L = 50 cm/sec ϕ = 1.04   P = 0.17 atm. $\eta = 0.51\ .\lambda/\sqrt{Re_\lambda}$ δ_L = 0.0269 cm

U (m/sec)	Grid No	u' (cm/sec)	L (cm)	λ (cm)	η (cm)	E_m (mJ)	[illegible] (cm)
6.1	1	15	0.40	0.37	0.076	3.5	[illegible]
"	2	16	0.51	0.41	0.081	2.5	1.9
"	1	29	0.27	0.20	0.040	5.3	[illegible]
"	2	30	0.31	0.24	0.045	5.0	2.1
"	3	32	0.40	0.36	0.054	4.5	2.0
"	4	27	0.62	0.46	0.063	4.0	[illegible]
"	3	55	0.24	0.18	0.028	5.0	[illegible]
"	4	50	0.37	0.29	0.038	5.2	2.05
"	5	52	0.50	0.41	0.044	4.7	2.0
"	6	56	0.62	0.46	0.045	5.5	2.15
"	7	58	0.80	0.58	0.050	5.0	2.20
"	4	80	0.24	0.19	0.024	5.3	[illegible]
"	5	76	0.32	0.23	0.026	5.5	[illegible]
"	6	78	0.40	0.34	0.032	7.0	[illegible]
"	7	83	0.51	0.37	0.034	7.5	[illegible]
"	5	107	0.18	0.18	0.020	5.5	[illegible]
"	6	110	0.23	0.20	0.022	6.5	[illegible]
"	7	103	0.29	0.23	0.024	8.5	[illegible]
15.2	4	196	0.24	0.13	0.012	8.5	[illegible]
"	5	185	0.33	0.15	0.013	9.0	[illegible]
"	6	205	0.40	0.20	0.015	8.5	[illegible]
"	7	190	0.51	0.23	0.017	9.0	2.6
"	6	336	0.18	0.12	0.009	10.0	[illegible]
"	7	345	0.23	0.15	0.011	8.5	[illegible]

It was not possible to include the following figures in the original version of this paper (presented at the Fifteenth International Combustion Symposium, Tokyo) due to the limitation on space. The data presented in these figures is, however, generally correlated by the derived expressions for the minimum ignition energy.

Figures 3a, 4a, 5a, 6a, 9a, 10a.

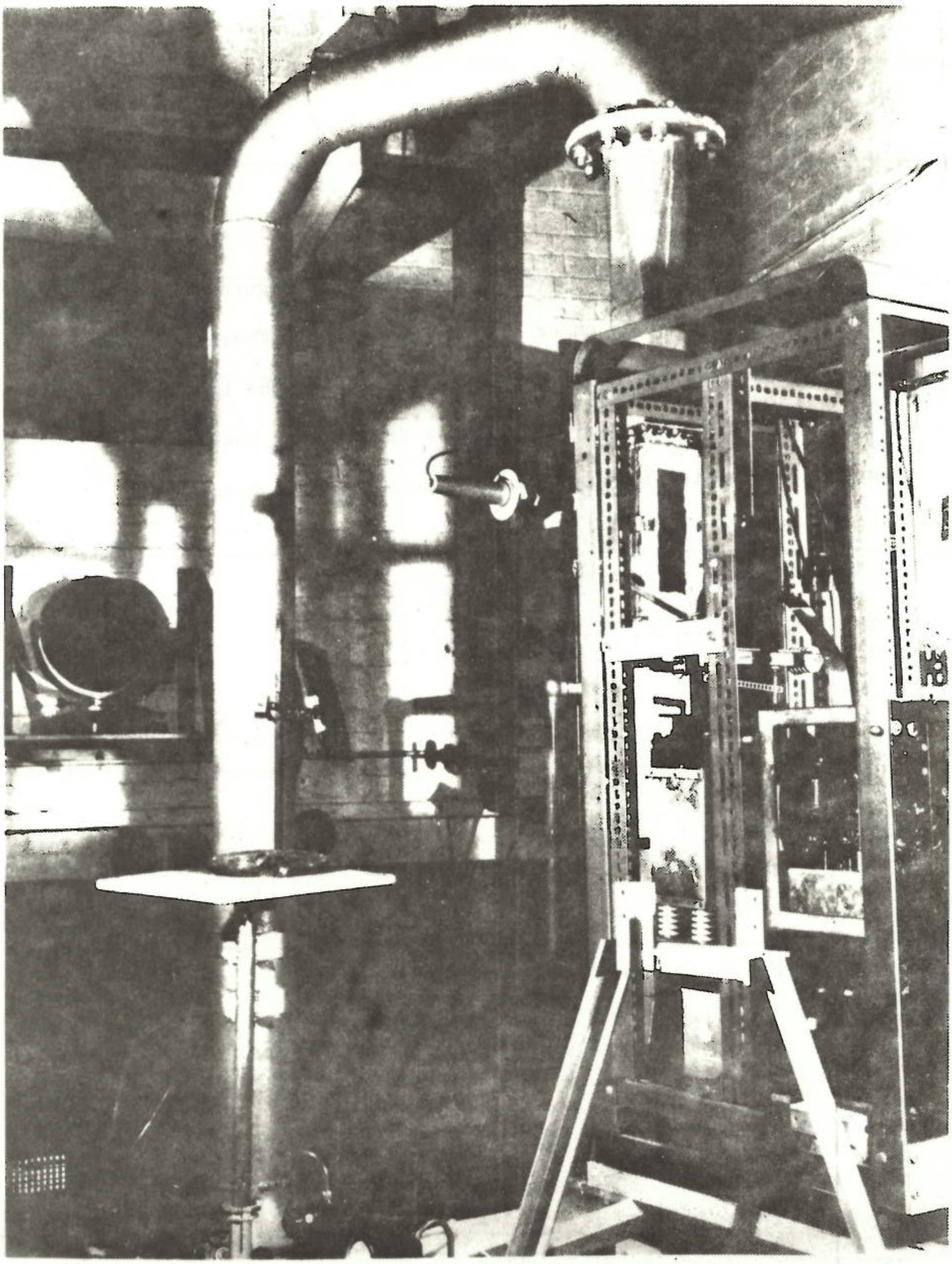

Plate I : Low Pressure Ignition Rig.

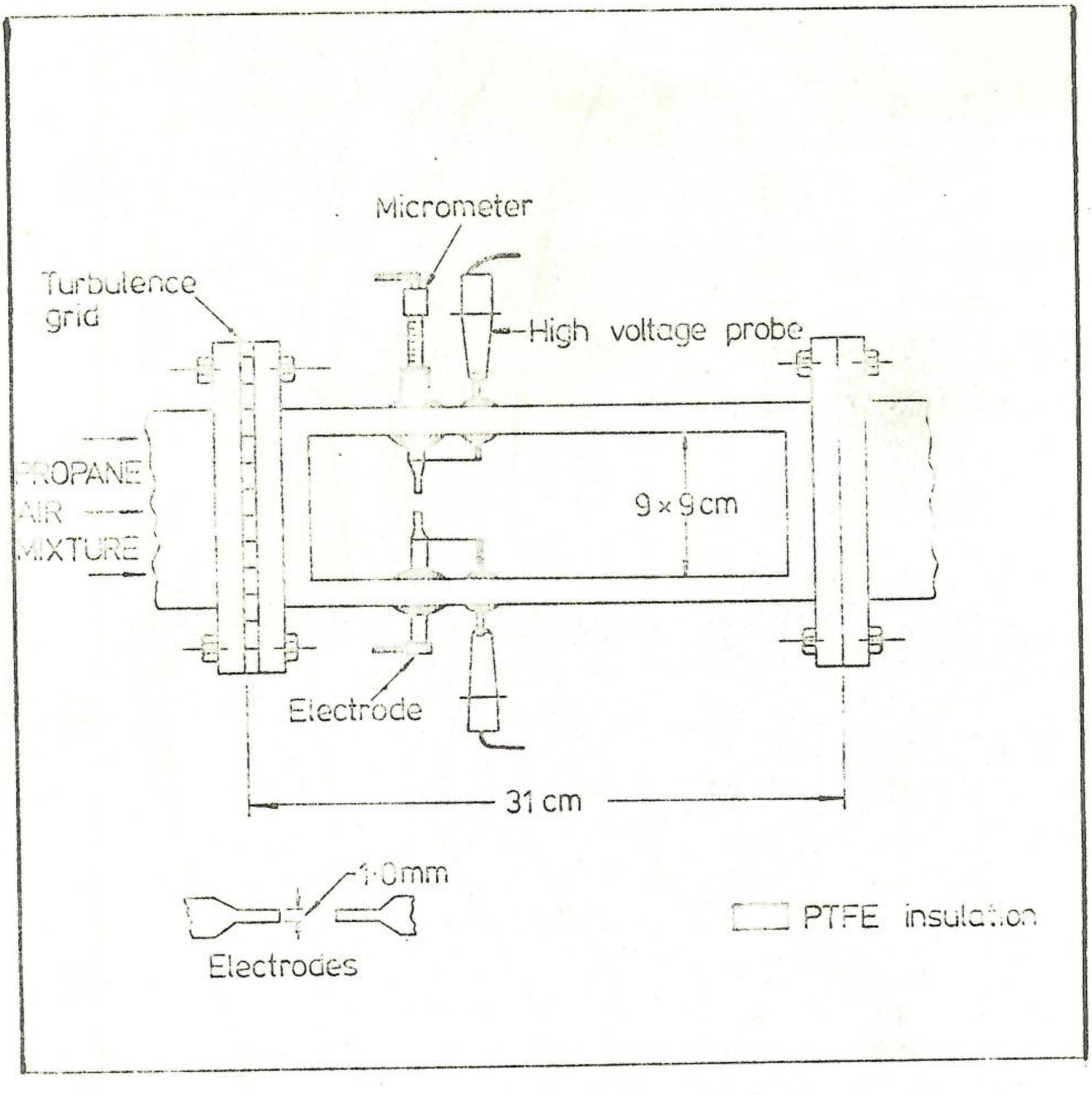

Figure 1 The working section.

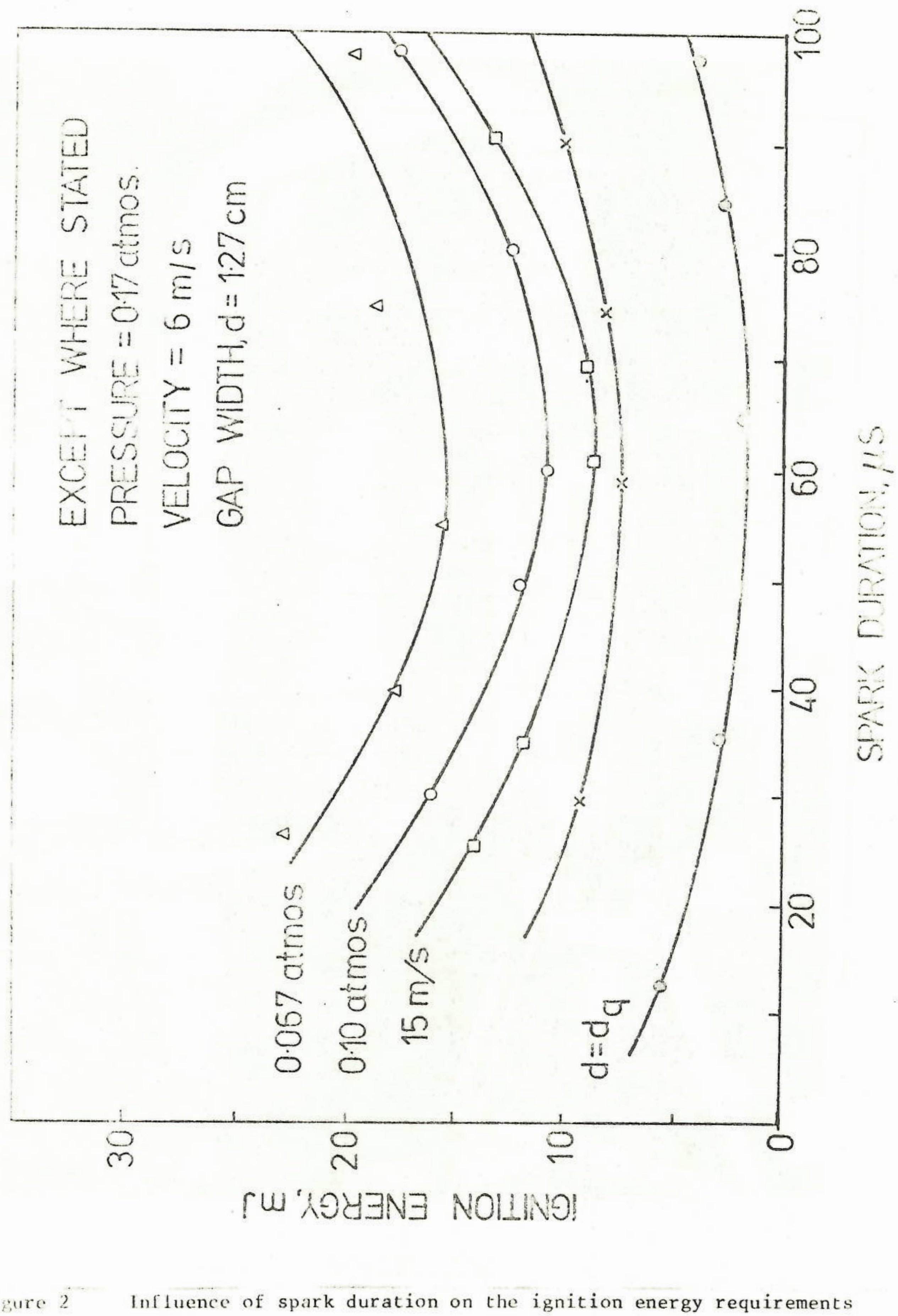

Figure 2 Influence of spark duration on the ignition energy requirements of stoichiometric propane/air mixtures.

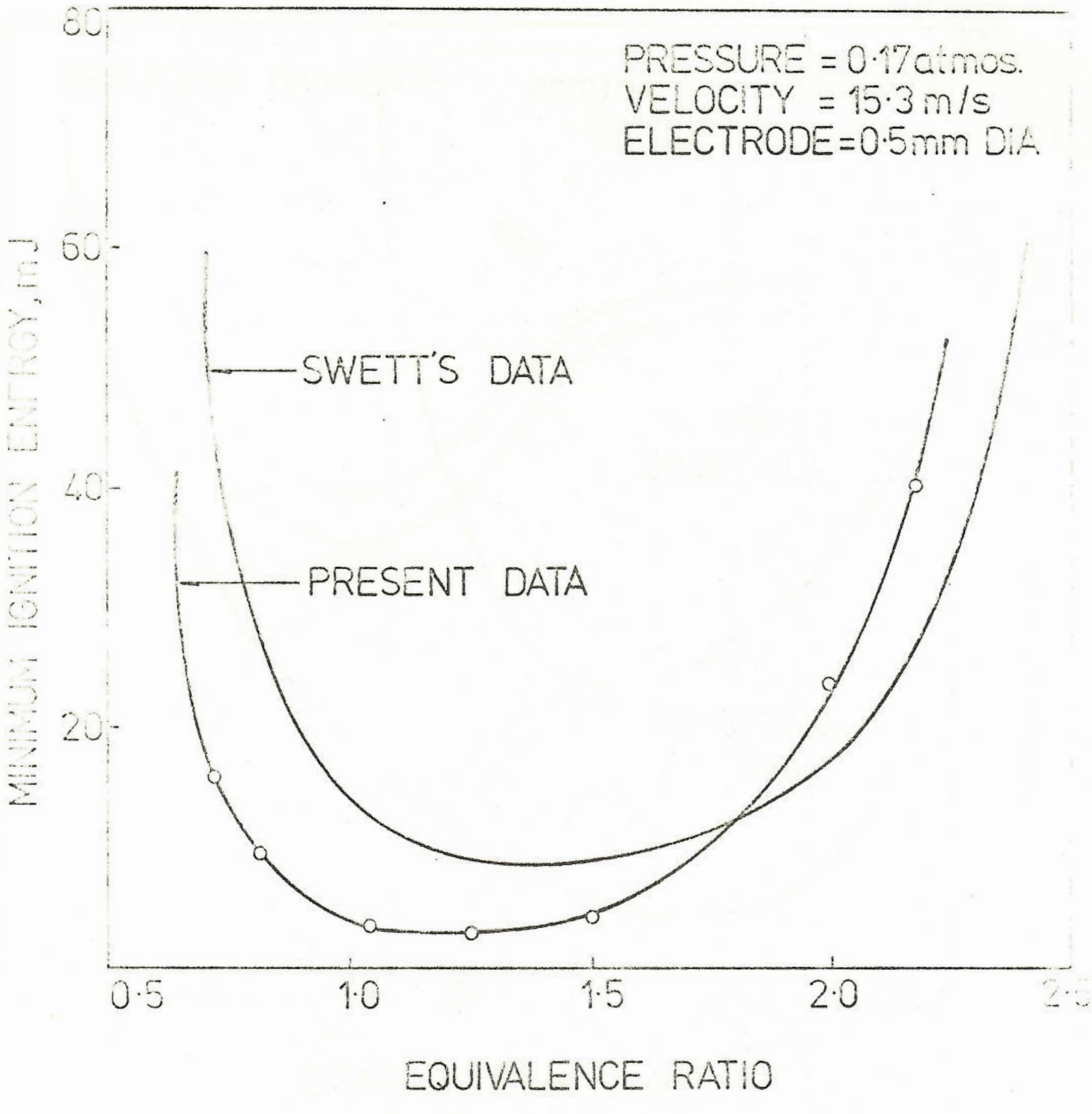

Figure 3 Influence of mixture strength on minimum ignition energy

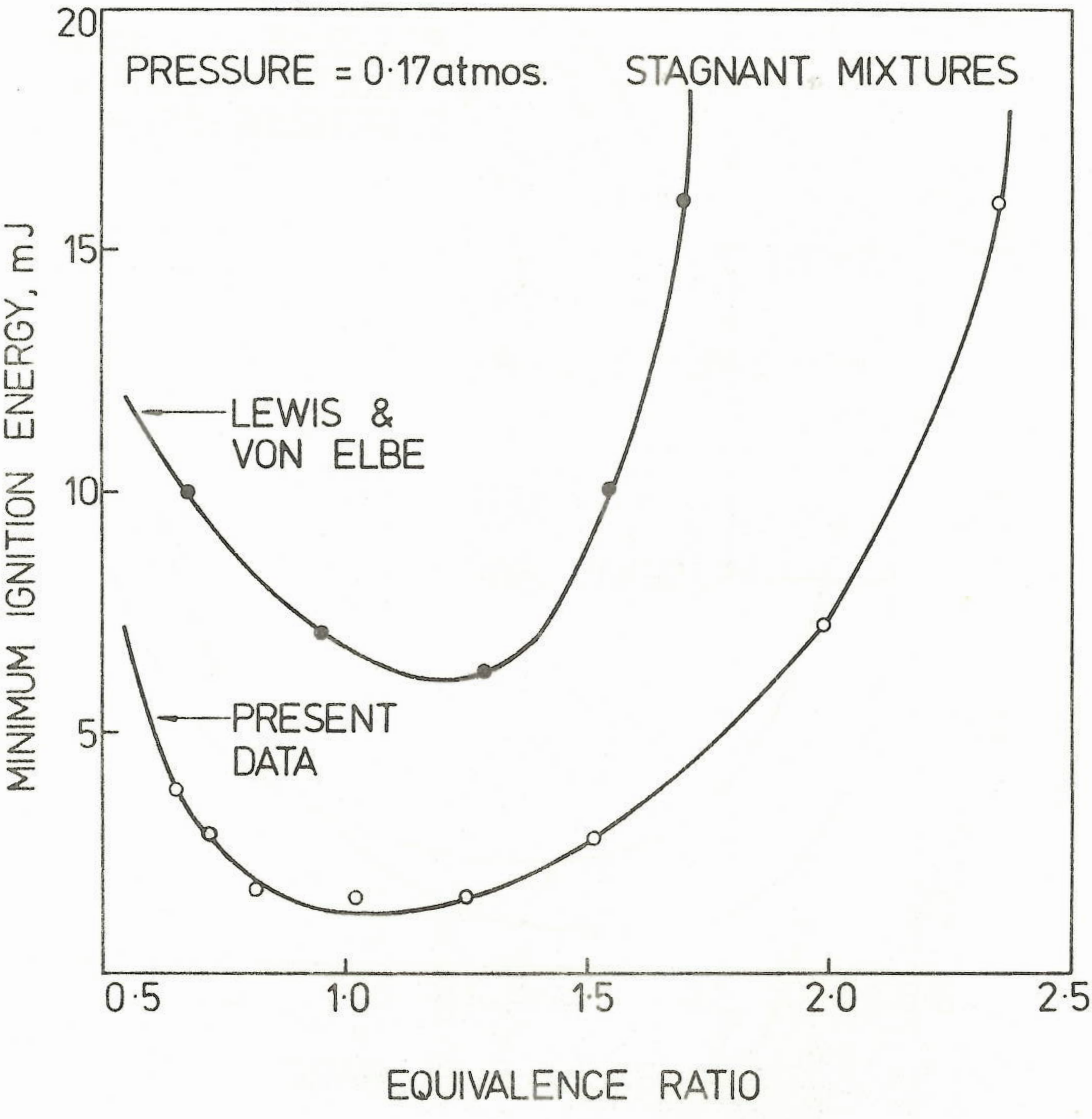

Figure 3a Comparison between Lewis & von Elbe's data and the present results under identical Ignition Conditions

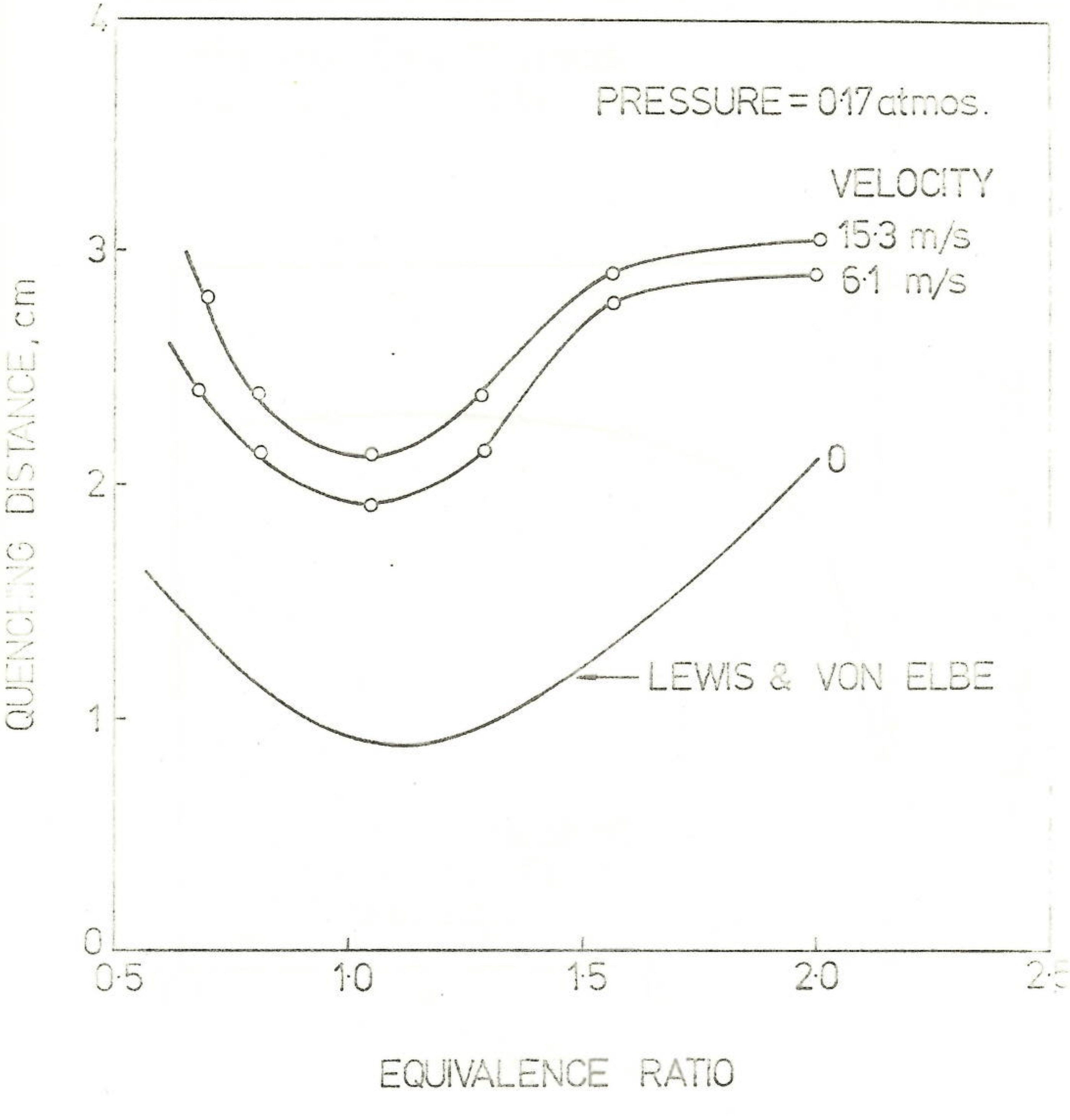

Figure 4 Influence of velocity and mixture strength on quenching distance

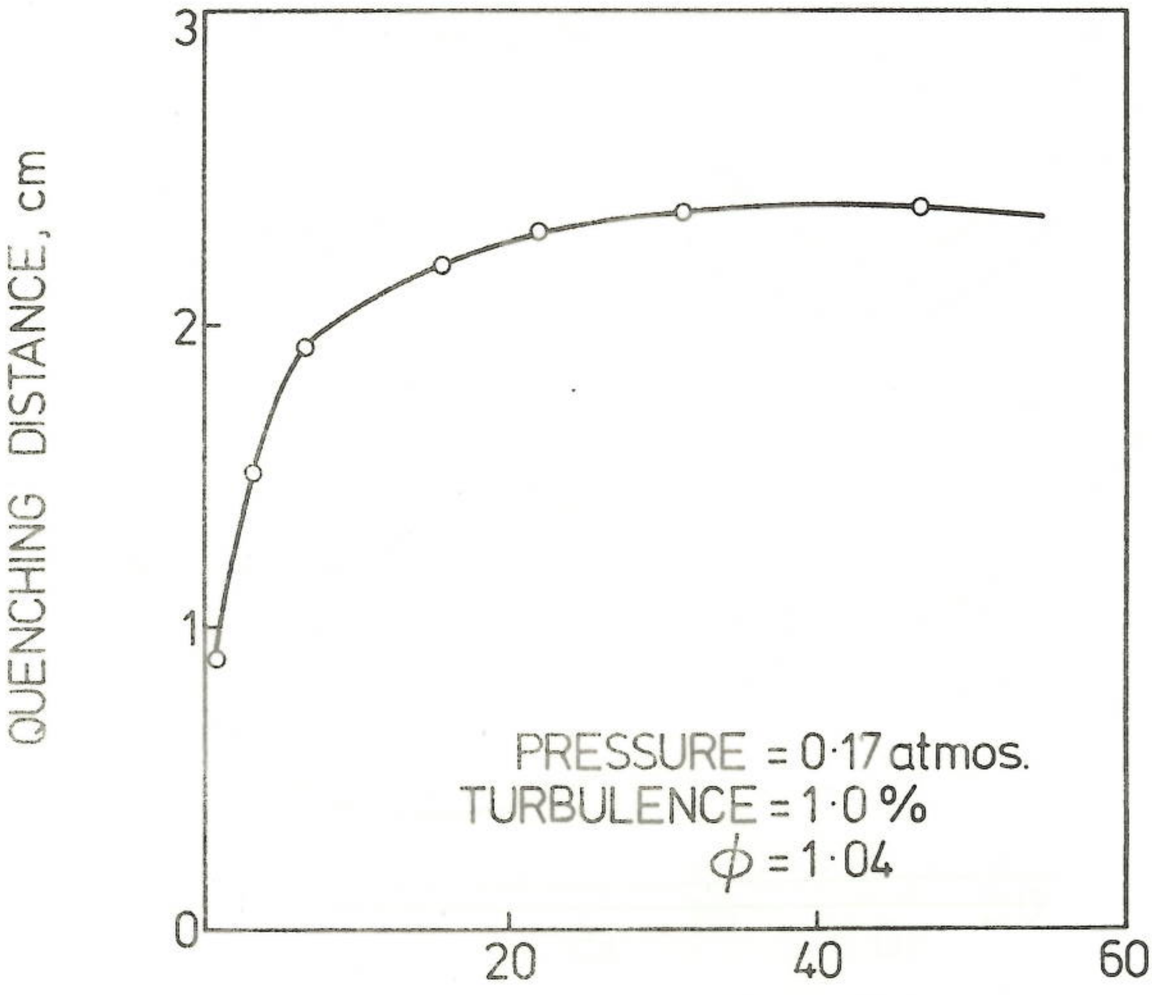

Figure 4a Influence of velocity ~~& mixture strength~~ on quenching distance for a stoichiometric propane/air mixture

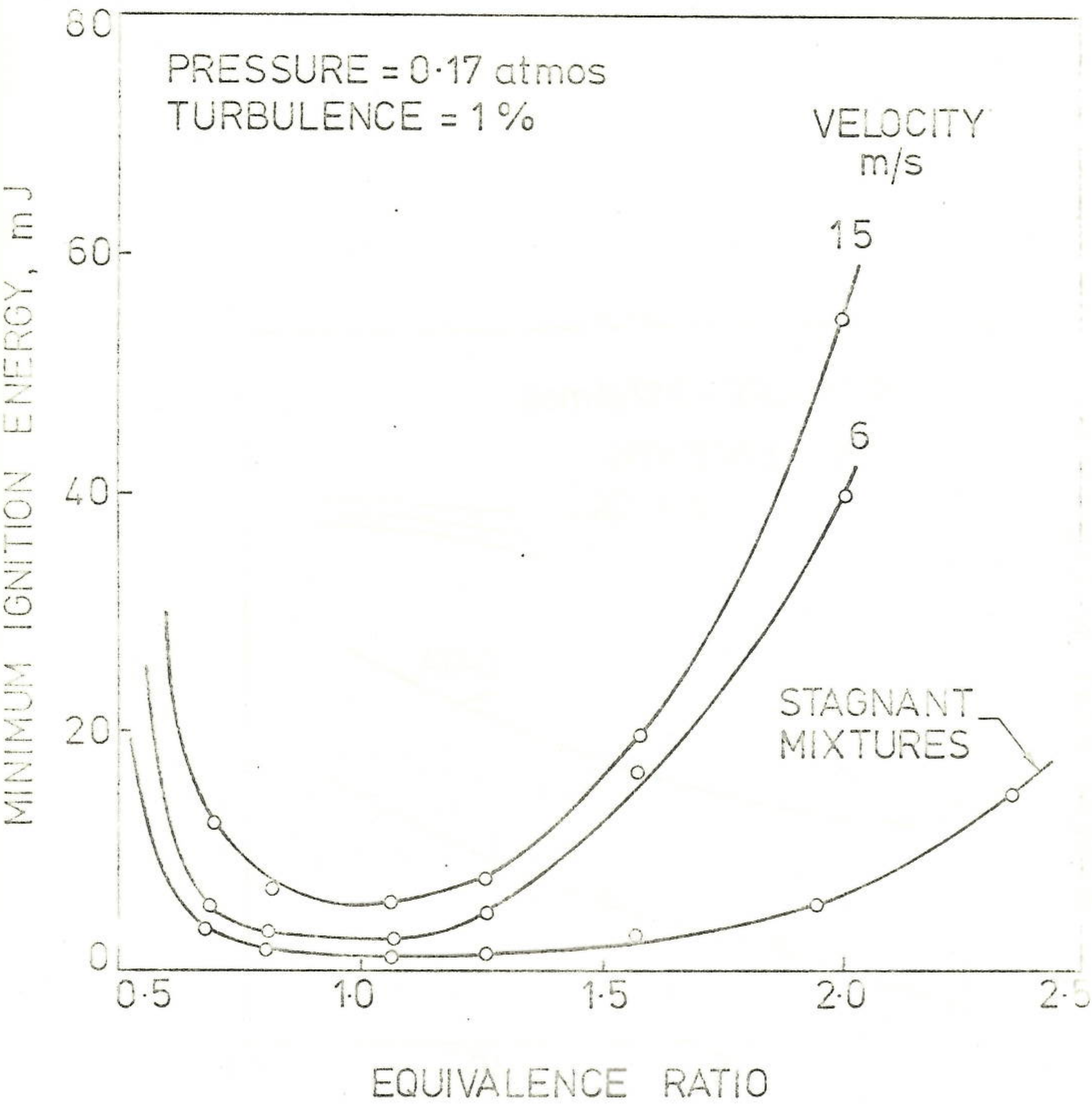

Figure 5 Graphs illustrating the adverse effect on ignition of increase in mainstream velocity

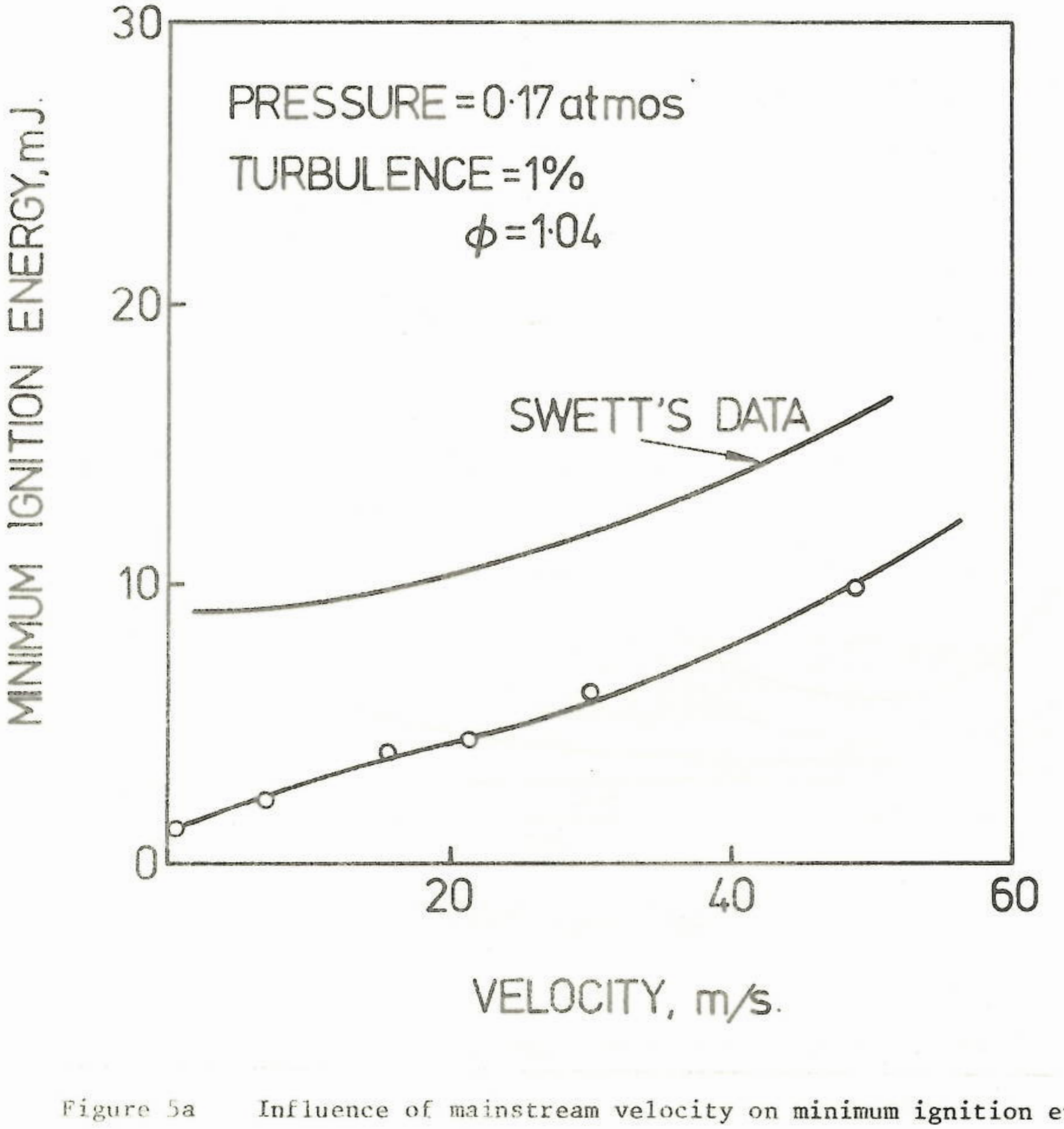

Figure 5a Influence of mainstream velocity on minimum ignition energy for a stoichiometric propane/air mixture

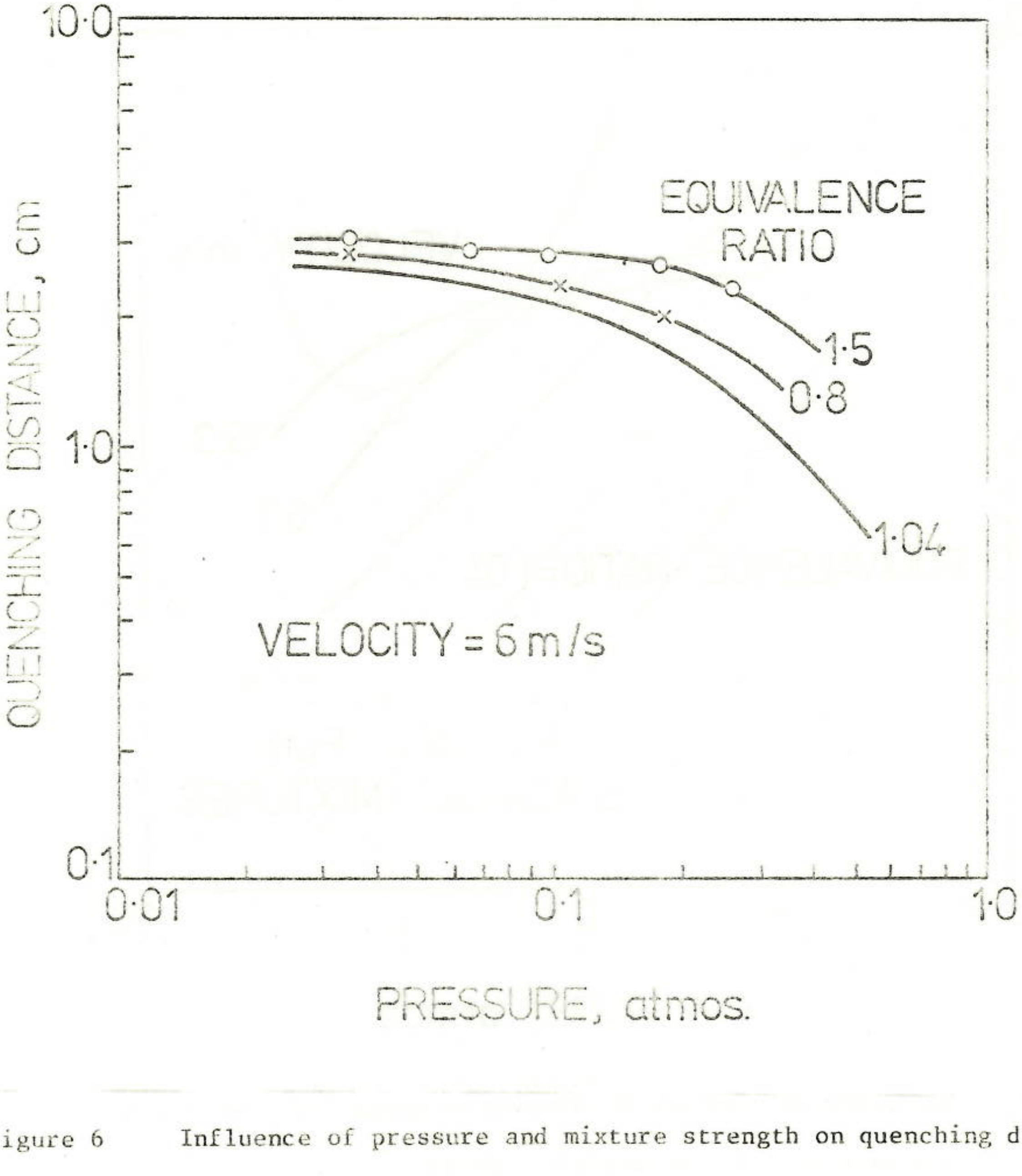

Figure 6 Influence of pressure and mixture strength on quenching distance

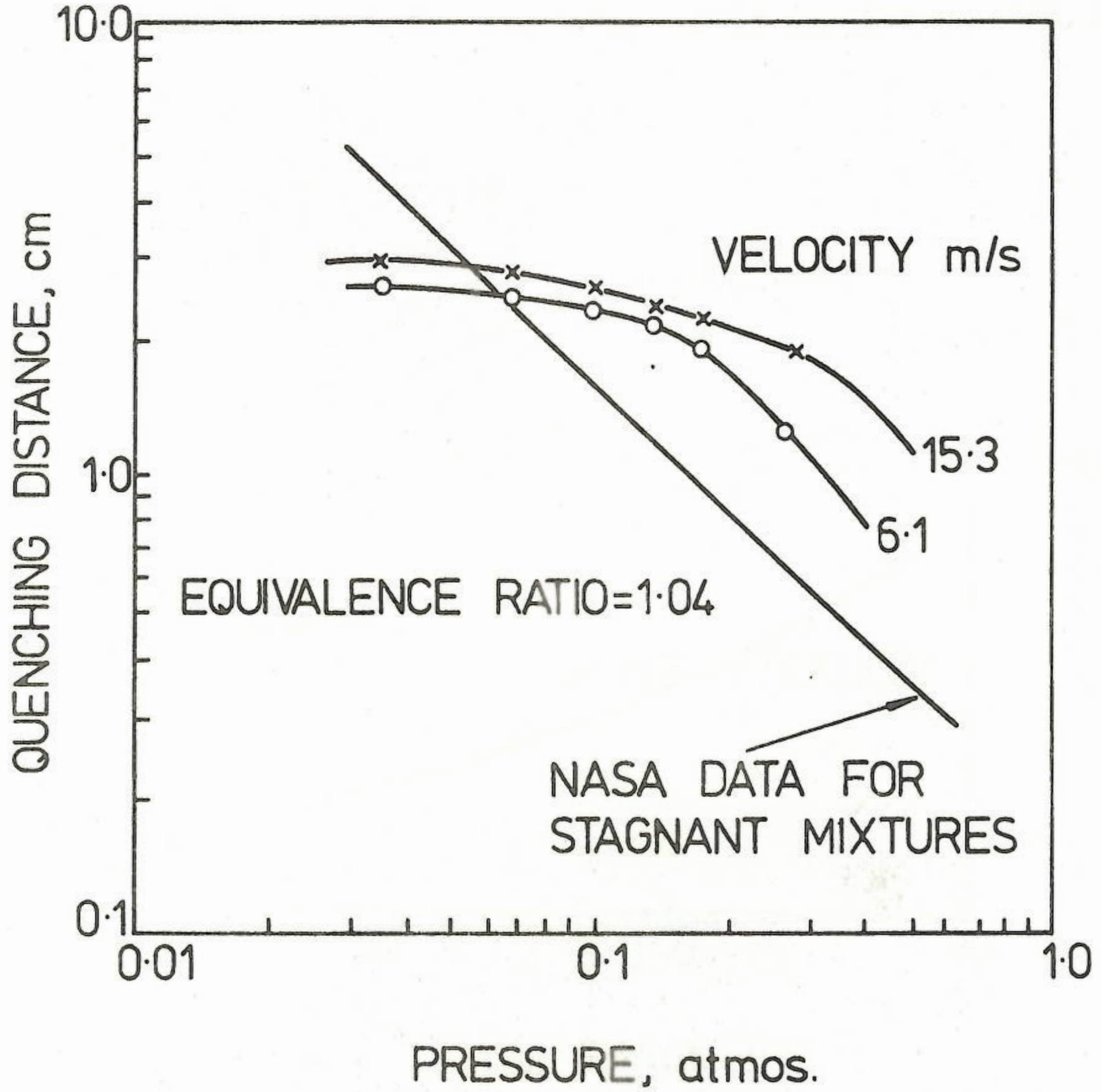

Figure 6a Influence of pressure & velocity on quenching distance for a stoichiometric propane/air mixture

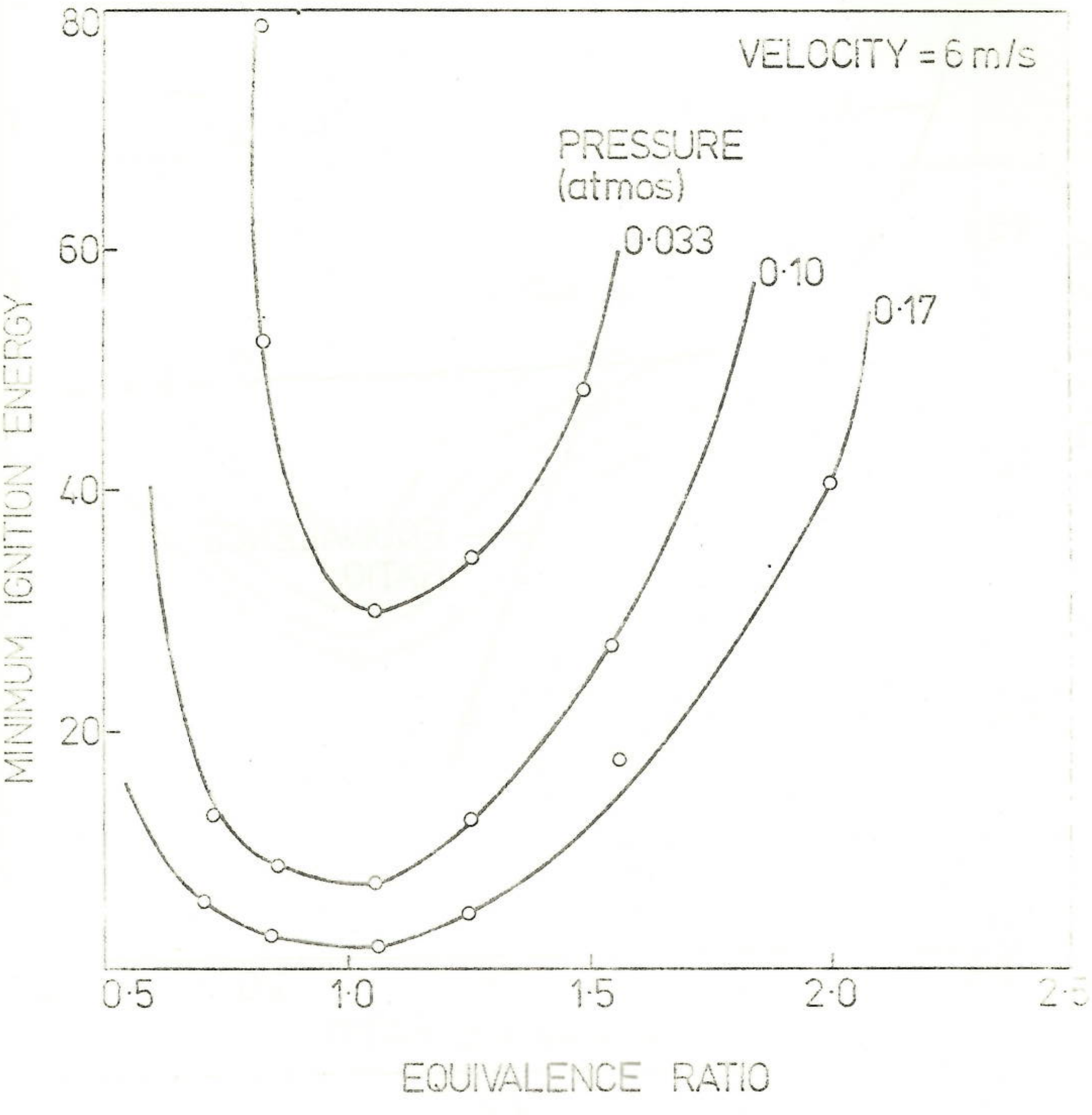

Figure 7 Influence of pressure and mixture strength on minimum ignition energy

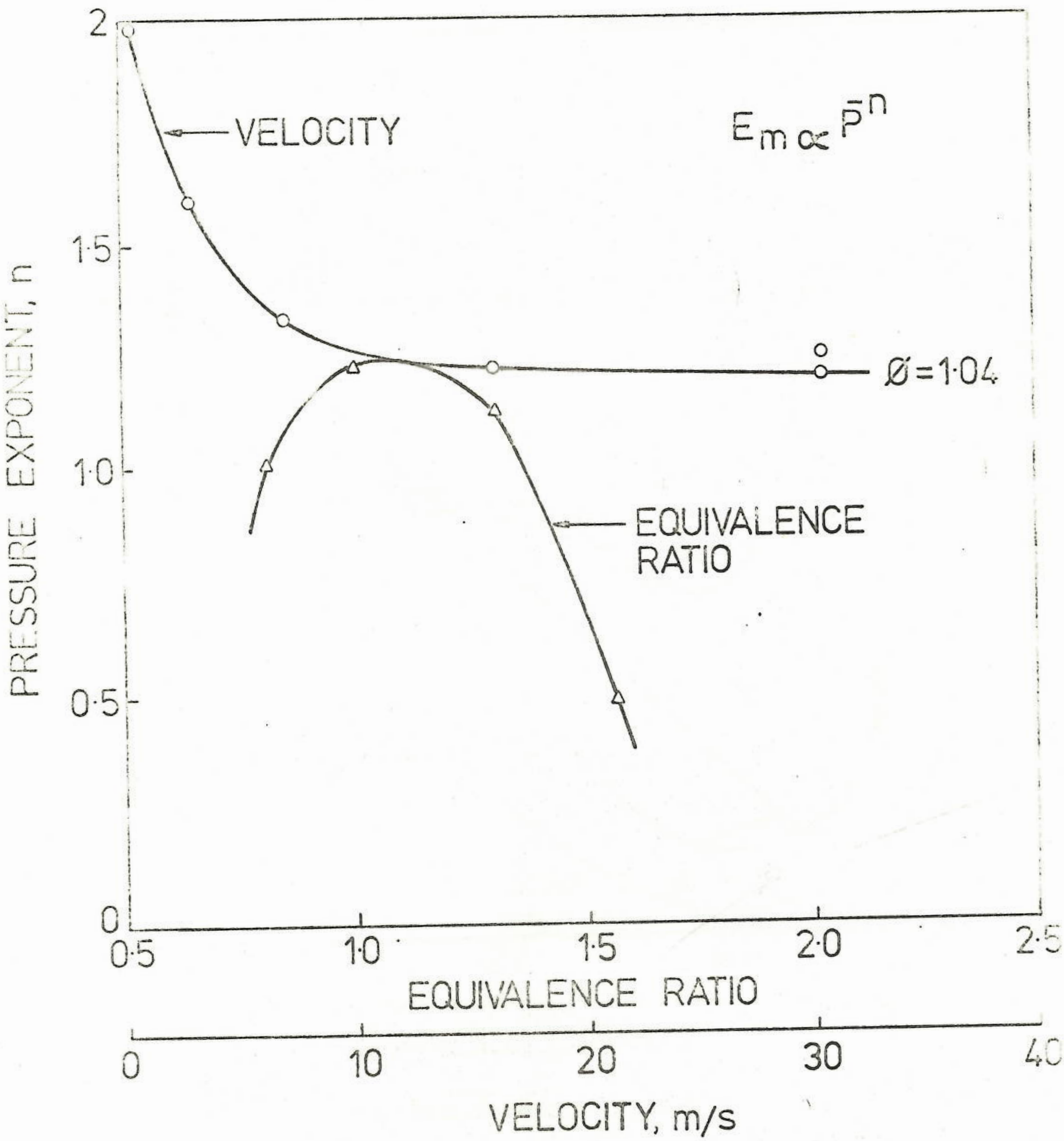

Figure 8 Pressure dependence of E_{min} as a function of velocity and mixture strength

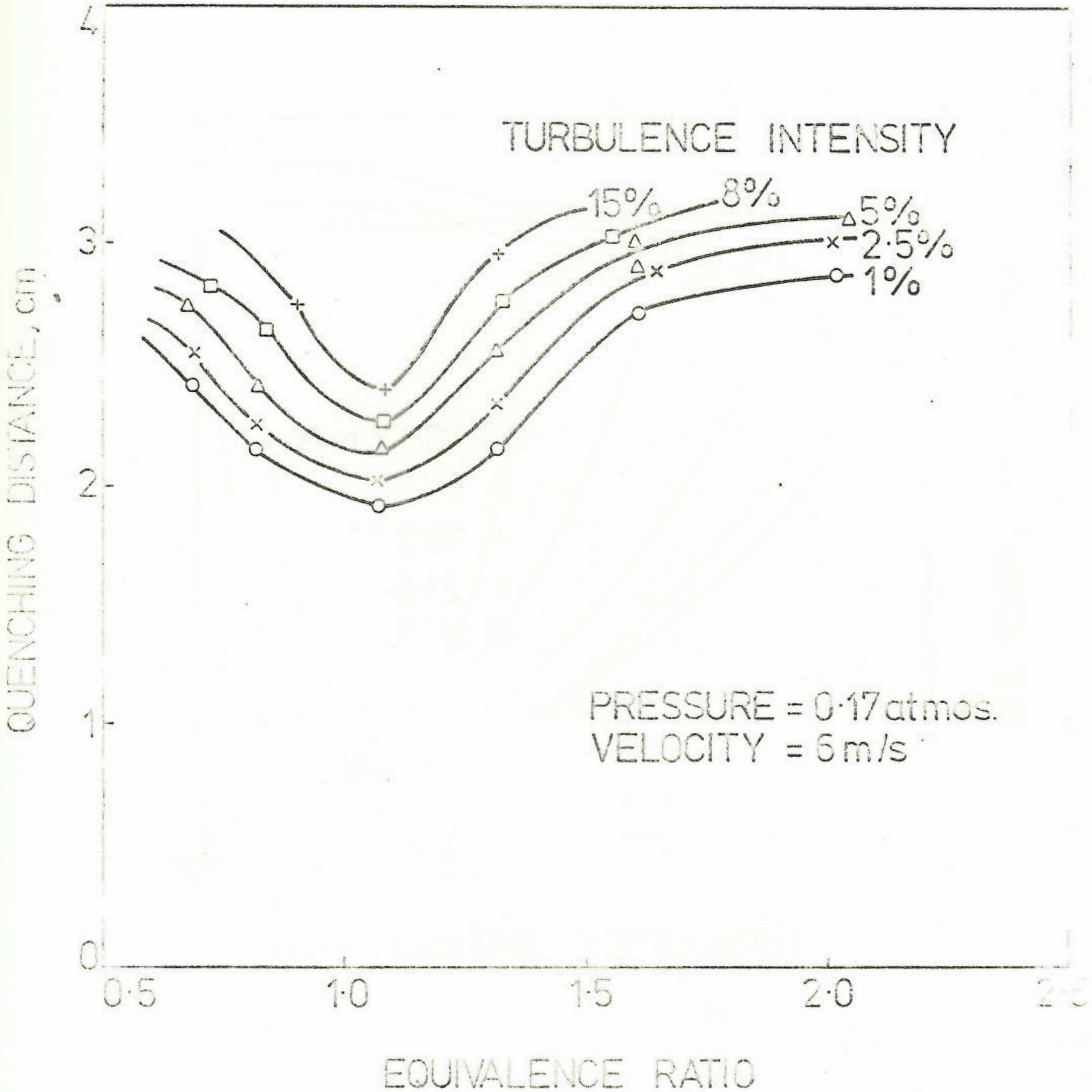

Figure 9 Graphs illustrating the effect of turbulence intensity on quenching distance

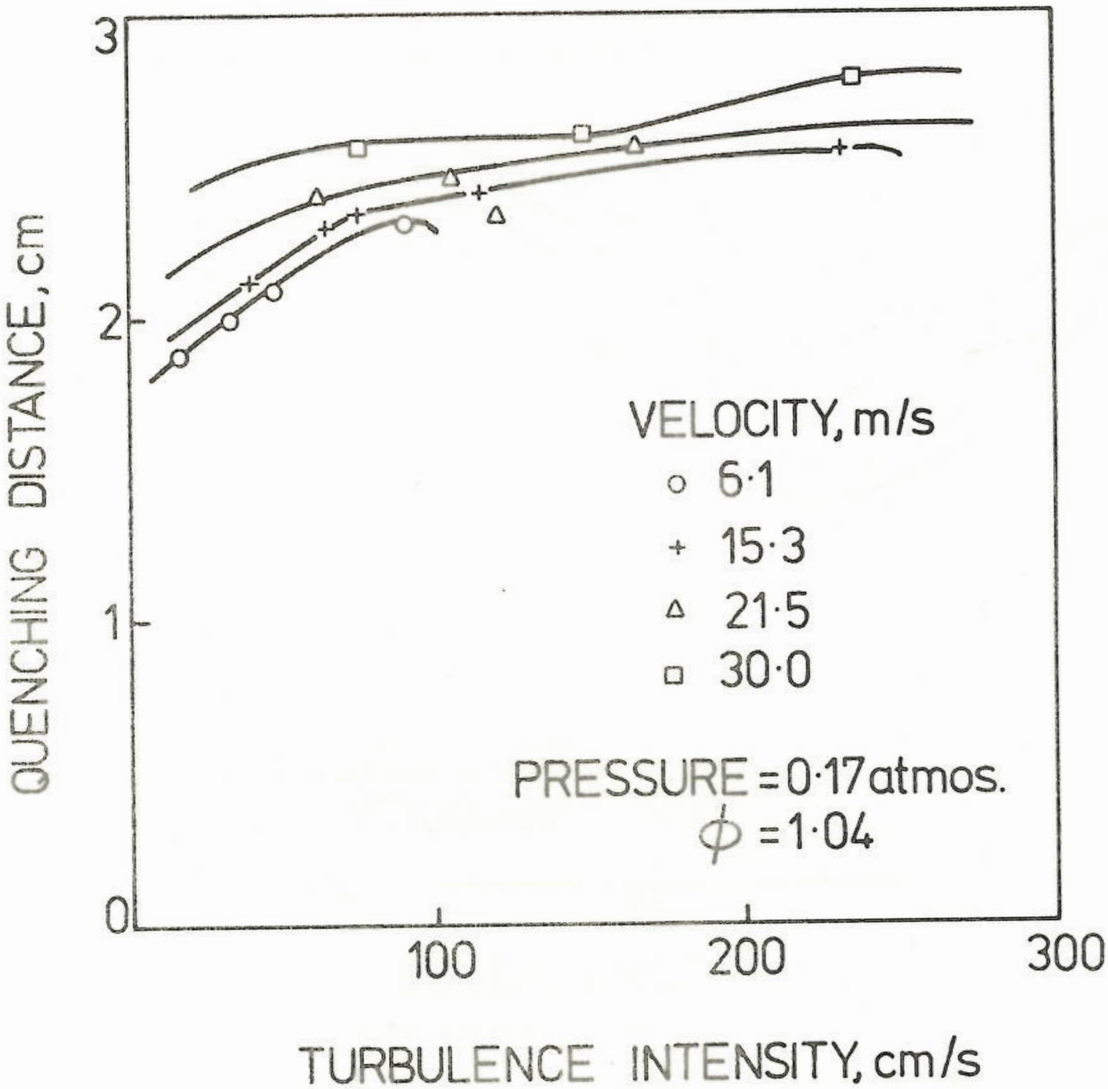

Figure 9a The effect of turbulence intensity on quenching distance for a stoichiometric propane/air mixture

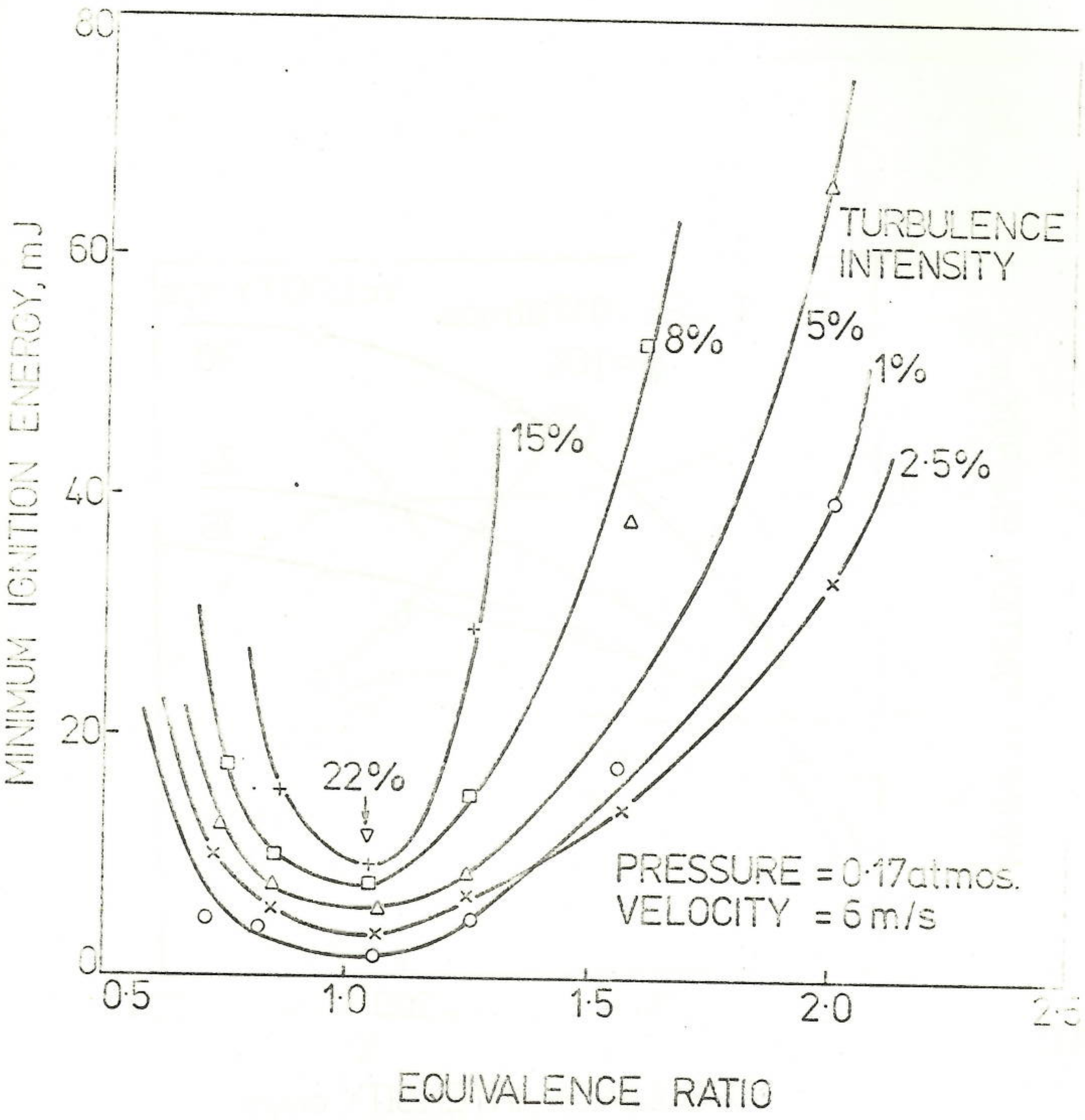

Figure 10 Graphs illustrating the effect of turbulence intensity on minimum ignition energy

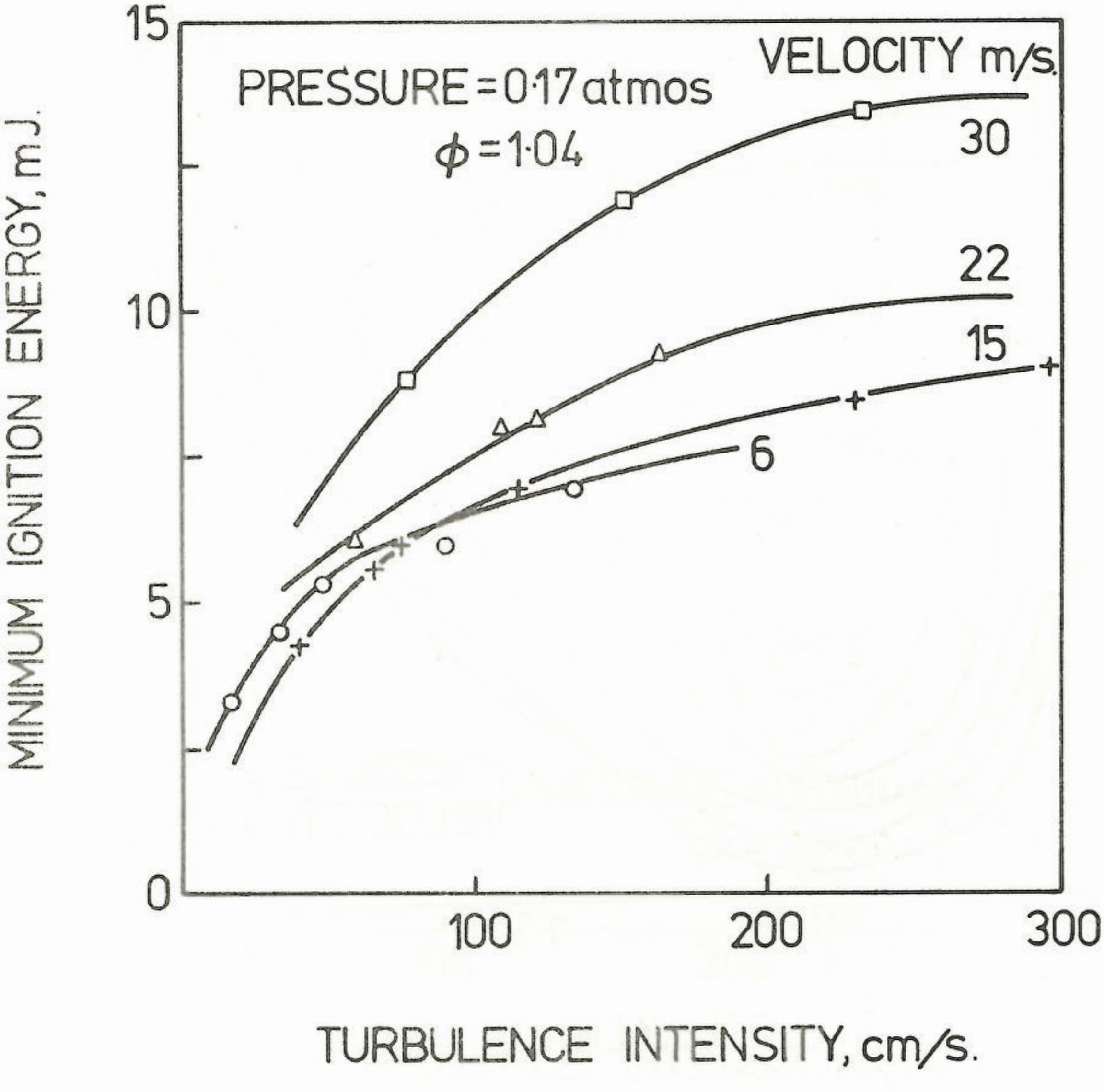

Figure 10a The effect of turbulence intensity on minimum ignition energy for a stoichiometric propane/air mixture

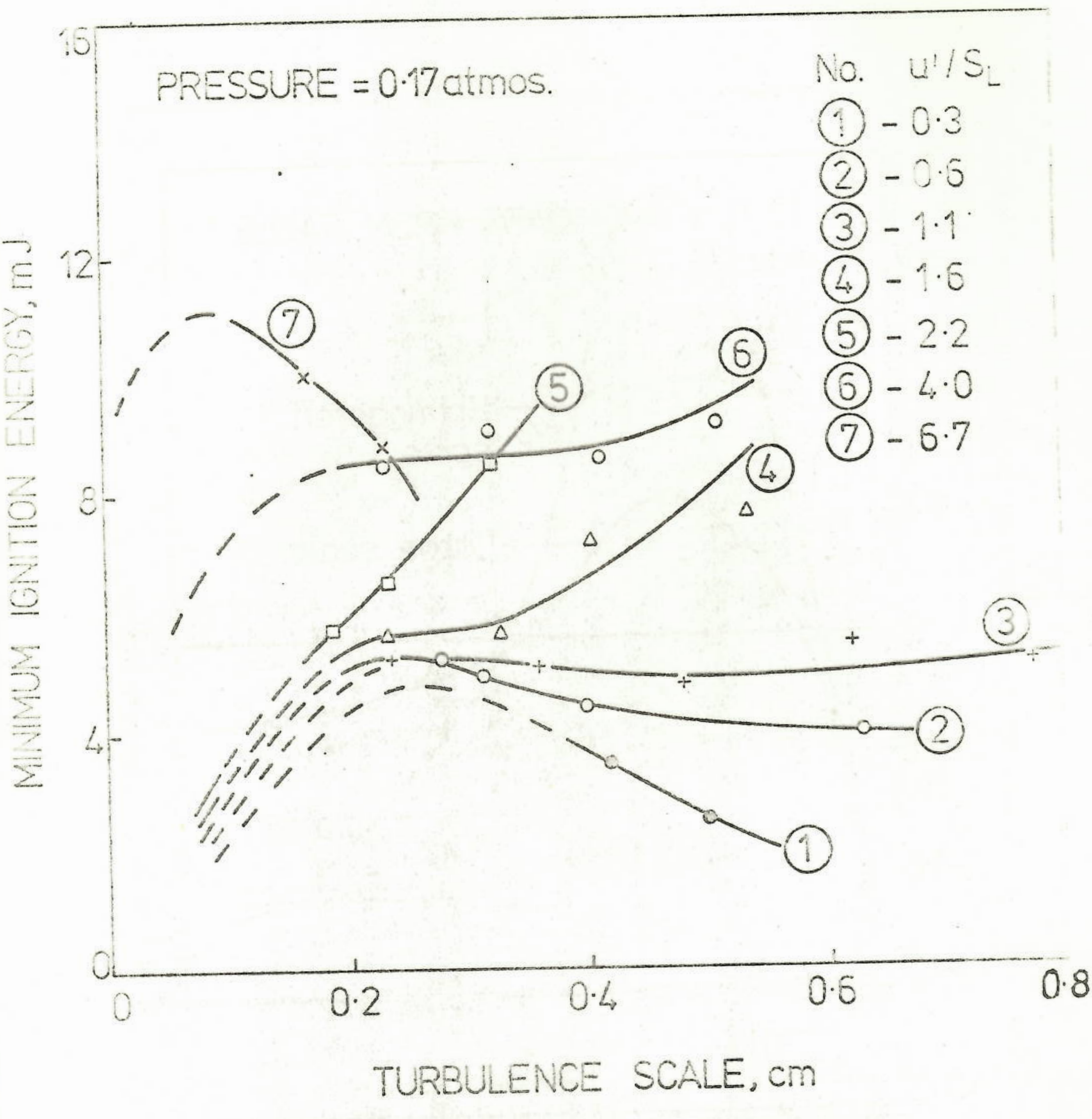

Figure 11 Influence of turbulence scale on minimum ignition energy

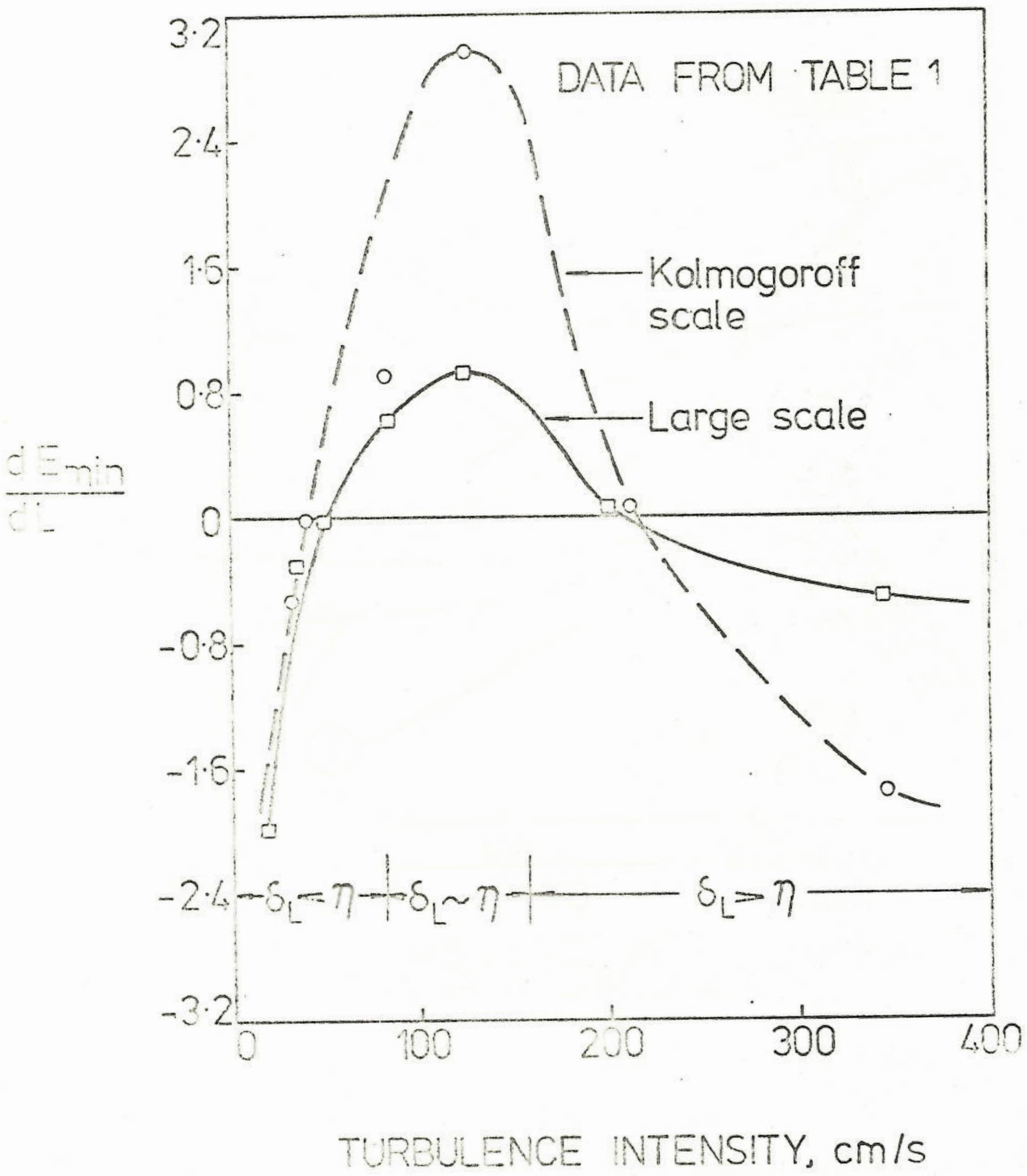

Figure 12 Graphs illustrating the effect of turbulence intensity on the dependence of E_{min} on L.

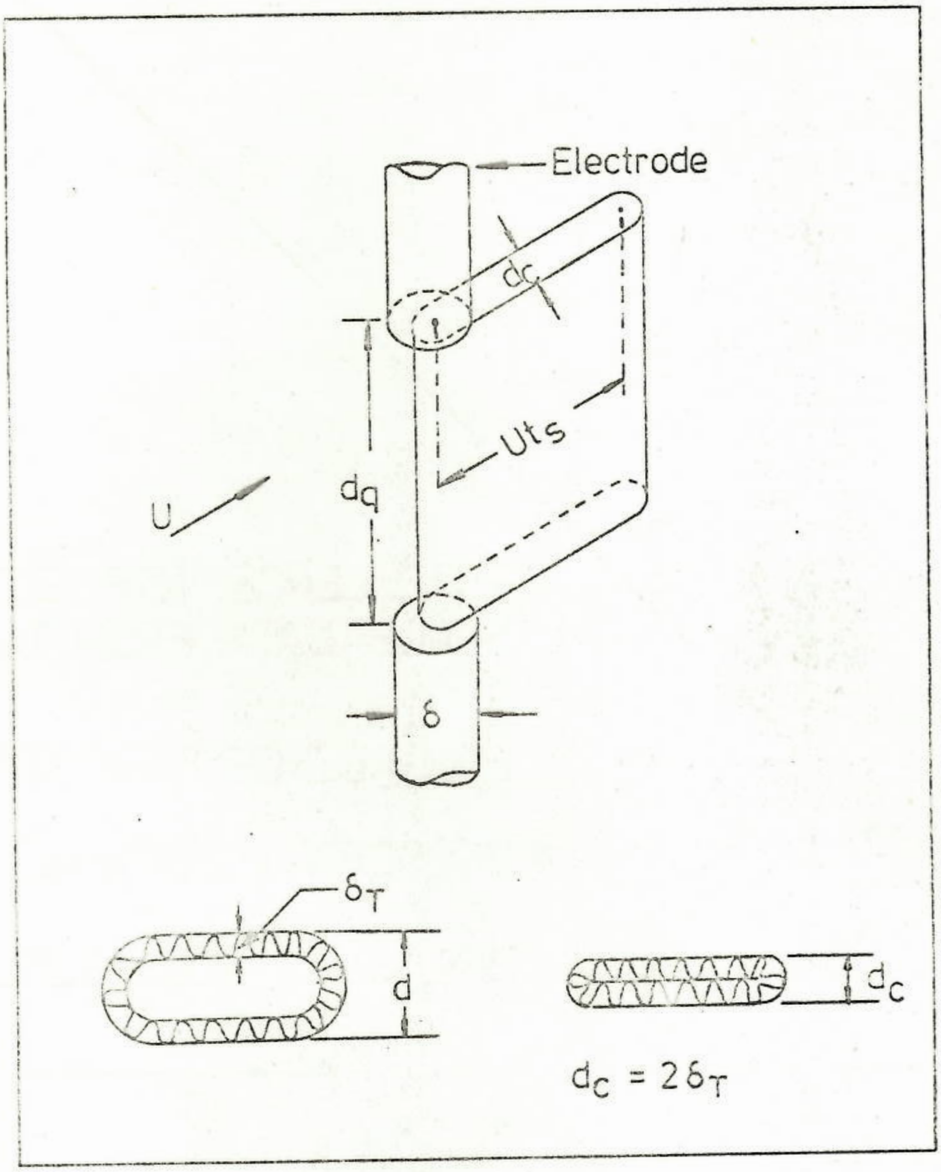

Figure 13   Proposed idealized model for formation of spark kernel

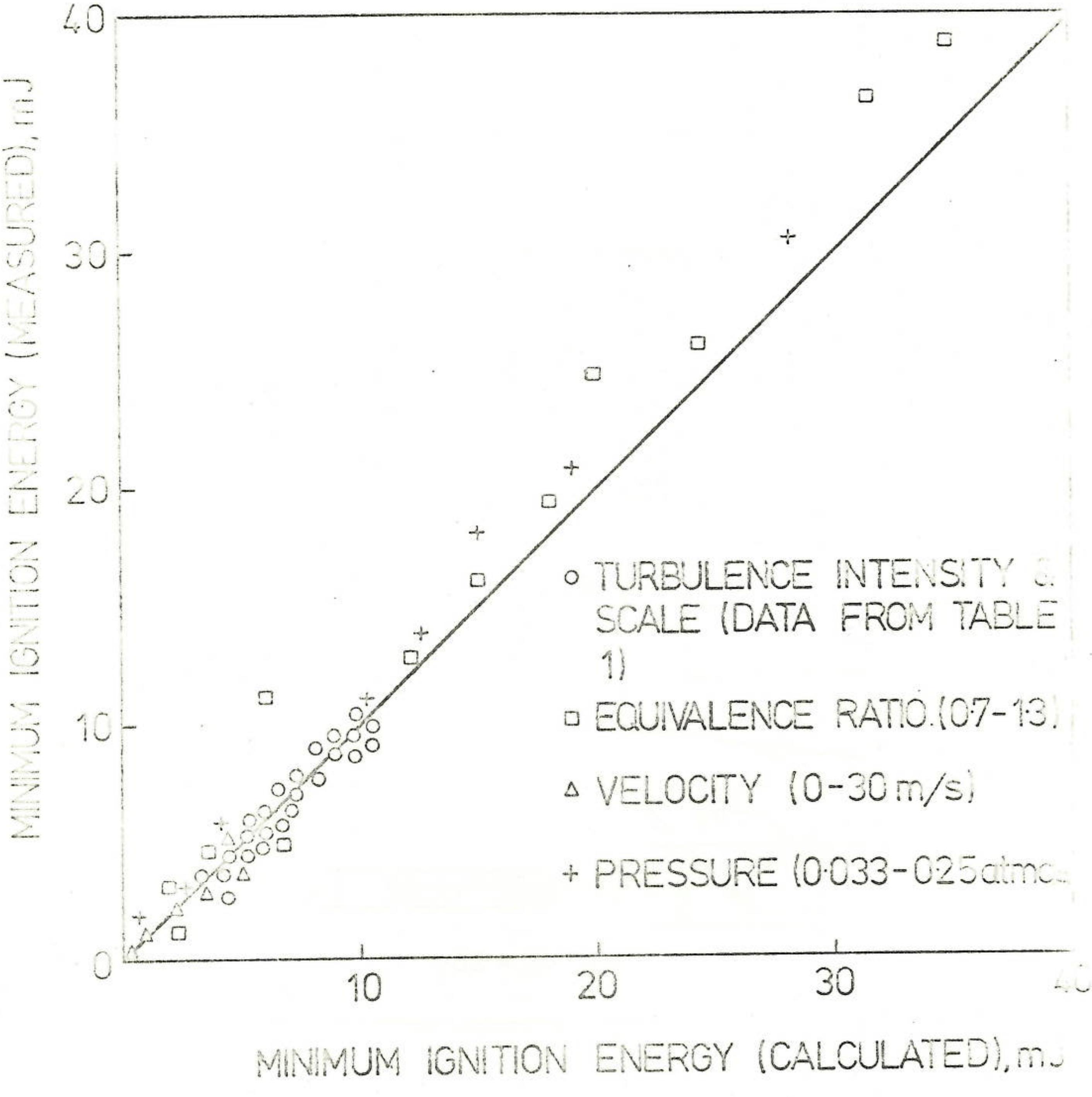

Figure 14 Comparison of calculated and measured values of minimum ignition energy