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On the minimum ignition energy (MIE) for propane/air

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ABSTRACT

A copy of the standard ASTM spark generator for determination of MIEs of gases and vapours was built and measurements to determine MIE of propane/air at normal atmospheric conditions were performed. However, the ASTM standard does not prescribe any statistical procedure for deriving MIE values from primary test data. We therefore adopted the "highest-possible-border-line" procedure proposed by Moorhouse et al. in 1974, and obtained a MIE of 0.48 mJ, which is very close to the 0.46 mJ found by these workers, as opposed to the classical Lewis and von Elbe value of only 0.25 mJ. One possible reason for the discrepancy could be the very low ignition probability of only 1% used by Lewis and von Elbe as their MIE criterion. However, when applying both linear and logistic regression analysis to our experimental data, the spark energies yielding 1% probability of ignition were found to be 0.40 ± 0.06 and 0.45 ± 0.08 mJ, respectively, which are both significantly higher than 0.25 mJ. This may indicate that the classical MIE values for gases and vapours published by Lewis and von Elbe (1961) are perhaps unnecessarily conservative.

1. Introduction

It seems that for more than half a century the classical MIE values provided by Lewis and von Elbe [1] for a wide range of mixtures of combustible gases and air have been widely used as standard reference values. For propane/air the value is 0.25 mJ. The numerous U-shaped curves for MIE as a function of mixing ratio of combustible gas/air published by these workers have gained wide general acceptance.

The present investigation came about as a result of an attempt to develop an electric spark generator for determination of MIEs of very ignition-sensitive dust clouds in air in the <1 mJ range. Because the experimental dust clouds used were transient, produced by a short blast of air, the appearance of the electric spark had to be synchronized with the appearance of the dust cloud. Therefore, a means of synchronization had to be incorporated into the spark generation circuit. The details of the first version of the generator developed for this purpose were published by Randeberg et al. [2]. The first MIE results were presented by Randeberg and Eckhoff [3]. However, as discussed by Eckhoff et al. [4], it appeared that Randeberg et al. [2] significantly underestimated the real spark energies produced by their circuit because of a previously undetected subtle additional energy supply to the spark channel before onset of the ignition process. In view of this finding it was necessary to redesign the spark generator in order to minimize and control this additional energy supply to the extent practically possible. In order to calibrate the re-designed circuit for generation of synchronized sparks, using premixed propane/air, it was decided to first measure MIE of premixed propane/air by means of the spark generator prescribed in the ASTM [5] standard, and then subsequently conduct similar experiments using the synchronized spark generator, and compare the results.

However, it then appeared that the measurements by means of the ASTM standard spark generator produced an MIE for premixed propane/air that differed significantly from the classical US Bureau of Mines value. This was considered of sufficient interest in itself to justify a closer investigation.

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2. The investigation of Moorhouse et al.

Moorhouse et al. [6] determined the MIEs for C_1 to C_7 hydrocarbon/air mixtures. On the whole their values were significantly higher than those reported by Lewis and von Elbe [1]. Because we were already working with propane/air in other contexts, we selected this mixture for a closer study. The MIE for propane/air at normal atmospheric pressure and temperature found by Moorhouse et al. is 0.46 mJ, whereas the value of Lewis and von Elbe [1] is 0.25 mJ. Moorhouse et al. pointed out that Lewis and von Elbe had adopted a very low ignition probability of only 1% as their MIE criterion, and suggested that this could be the reason for the discrepancy. The alternative approach adopted by Moorhouse et al. was to draw the highest possible border line through the array of

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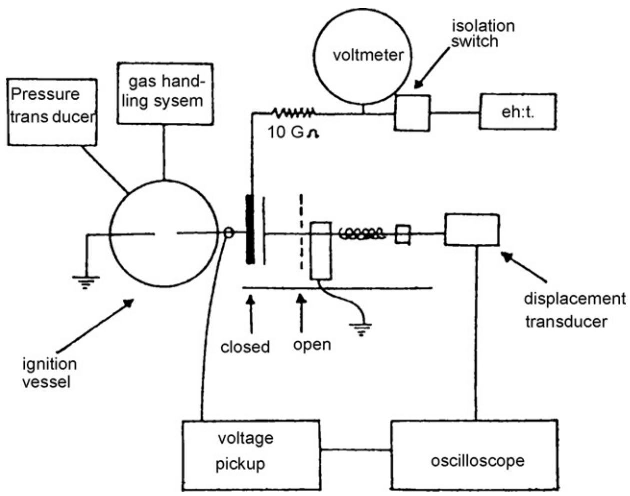

Fig. 1. Block diagram of the expanding-plate-capacitor electric spark generator used by Moorhouse et al. [6].

experimental ignition/no ignition points versus propane/air mixing ratio, below which there were no ignitions ("a boundary below which no ignitions were observed"). The minimum value of this, mostly U-shaped, border line was taken as the MIE.

Moorhouse et al. obtained their electric sparks by means of the variable-air-capacitor circuit developed by Cheng [7], which differs from the ASTM standard circuit used in the present investigation. Their circuit is illustrated in Fig. 1.

This is basically a simple RLC circuit with $L \approx 1\ \mu$H. The external circuit resistance was negligible compared to the average spark resistance. The capacitances were in the range 19–64 pF, and typical spark signatures were damped oscillations of about 10 MHz and 1 μs duration. The capacitor consisted of two 100 mm × 200 mm metal plates, one fixed, the other movable. The fixed plate was connected to the high-voltage electrode in the explosion vessel whereas the movable plate was connected to the other, earthed electrode. When the fixed plate had been charged from a high-voltage source, the spring loaded movable plate was released to become displaced rapidly outwards from its closest distance from the fixed plate (about 1 mm). This caused a decrease of the capacitance and a corresponding increase of the voltage across the capacitor, and hence across the spark gap. A discharge between the electrodes occurred as soon as the voltage had risen to the breakdown voltage of the spark gap.

During plate separation the voltage U across the plates will increase and the capacitance C of the plate system decrease according to

$$U_1C_1 = U_0C_0 \rightarrow U_1 = \frac{U_0C_0}{C_1} \qquad (1)$$

where the index 0 refers to the situation before plate separation and the index 1 to the situation at spark breakdown at some point during separation. By measuring the position of the movable capacitor plate at the moment of spark-over by a displacement transducer, the capacitance C_1 at spark-over can be calculated by simple basic theory. Then, if the residual energy left on the capacitor after spark-over is negligible in comparison to the spark energy, the latter equals

$$E = \tfrac{1}{2}C_1U_1^2 \qquad (2)$$

which, by inserting Eq. (1) in (2), contains only known quantities as follows:

$$E = \frac{1}{2}\frac{U_0^2C_0^2}{C_1} \qquad (3)$$

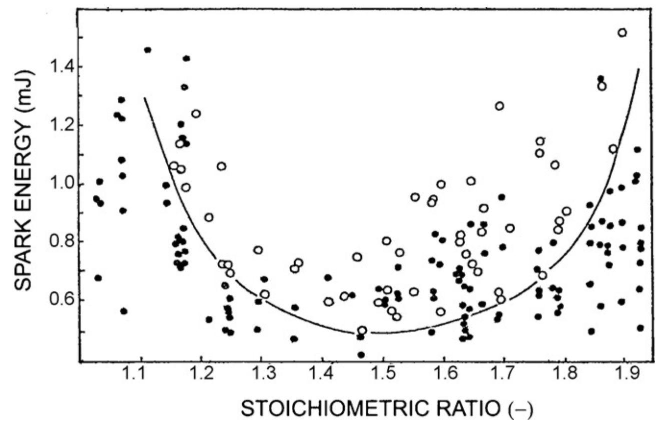

Fig. 2. Electric-spark-ignition diagram for n-pentane at 22 °C and 1 bar(g). Electrode separation: 2.2 mm; (●) non-ignition; (○) ignition. From Moorhouse et al. [6].

Moorhouse et al. determined their MIEs by varying the fuel/air ratio and the spark energy over wide ranges until a borderline between ignition and no-ignition could been identified. Fig. 2 illustrates the method. In the case shown, with pentane/air at atmospheric pressure, the minimum of the U-shaped curve is about 0.5 mJ, and hence this was taken as the MIE of pentane/air at atmospheric pressure and ambient temperature. For propane/air Moorhouse et al. [6] found the value 0.46 mJ, when using the same data reduction procedure as illustrated in Fig. 2.

3. Experimental apparatus and procedures

The block diagram of the standard ASTM [5] electric spark discharge circuit used in the present investigation is shown in Fig. 3. An isolating resistor of at least 1 TΩ is required to ensure a sufficiently large time constant for charging of the comparatively small energy storage capacitors. The spark gap voltage at spark-over was measured by means of an electrostatic voltmeter. With a simple electrostatic voltmeter, a separate divider resistor of at least 100 TΩ is required. In our case the voltmeter contained an integrated field mill representing an internal DC resistance of even more than 100 TΩ. Hence, our external divider resistor was only 330 kΩ. Our voltmeter contributed a small capacitance of about 2 pF in parallel with the main energy storage capacitor, which had to be accounted for when calculating the spark energy.

A cross-section of our explosion vessel is shown in Fig. 4. The vessel is cylindrical and made of hard transparent plastic. The internal diameter is 40 mm and the height 156 mm, corresponding to a net internal volume of 200 cm^3. A locking ring for fixing a paper cover is placed at the top of the vessel. Two 1.6 mm flat-ended tungsten electrodes fitted with glass flanges are located at the centre of the tube. One electrode is fixed, the other adjustable, allowing adjustment of the gap distance between the electrodes. The circular flanges of borosilicate glass have a diameter of 15 mm and a thickness of 3.0 mm. The flanges are fastened to the electrodes with Araldite.

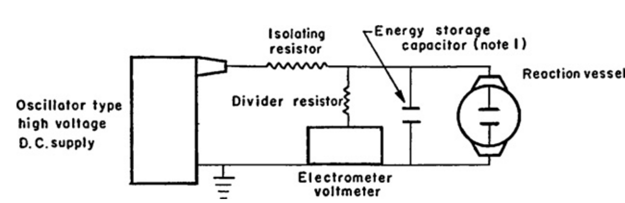

Fig. 3. Block diagram of standard ASTM electric spark generator for measurement of MIE for gases and vapours used in the present investigation. From ASTM [5].

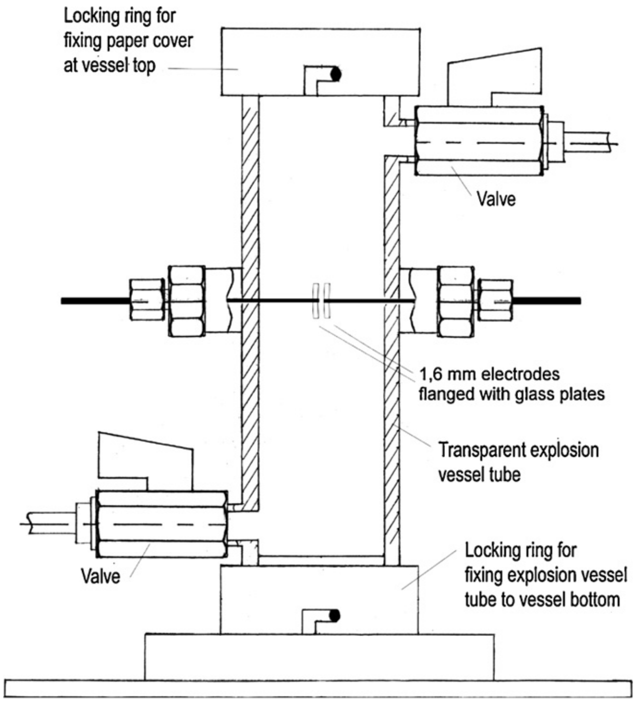

Fig. 4. Cross-section of explosion vessel with centrally located flanged electrodes, used in the present investigation.

When an ignition experiment was to be performed the explosion vessel was first flushed with the desired propane/air mixture by passing it through the entrance valve at the vessel bottom, leaving the valve at the top open. The desired mixing ratio of the propane/air mixture entering at the bottom was ensured by continuous measurement of the propane content, either directly by an IR-absorption instrument, or indirectly by measuring the oxygen concentration in the mixture by means of a very accurate oxygen sensor. The flushing was continued until the propane concentration at the outlet at the vessel top had become approximately identical with that at the inlet. The two valves were then closed.

Then the spark generator was triggered. If spark-over was not obtained at the first trial, triggering was repeated with 15–20 s intervals until spark-over occurred. The interval of 15–20 s was necessary to ensure that the energy supplied to the energy storage capacitor by the preceding attempt had dissipated. The spark energy was basically varied by varying the value of energy storage capacitor. Whenever spark-over was obtained it was observed whether or not ignition occurred.

4. Experimental results and discussion

The experimental ignition data for propane/air obtained in the present investigation are reproduced in Fig. 5 together with the highest possible borderline through the data points, below which there are no ignition points. The lowest energy at which ignition was obtained in all the experiments was 0.48 mJ. This occurred at a propane concentration of about 5.2 vol.%. However, as Fig. 5 shows, the bottom of the U-curve between about 4.2 and 5.5 vol.% was comparatively flat. A significant feature of the highest possible borderline found in the present investigation is the very steep rise of the curve on the leans side at about 4.2 vol.% propane. This is due to the glass flanges on the electrodes, which are in accordance with the ASTM [5] standard. With a spark gap length of 2.0 mm, the flanges makes spark ignition virtually impossible with leaner mixtures than 4.2 vol.% propane. In Fig. 6, the highest possible borderline in Fig. 5 is compared with that of Moorehouse et al., and with the 0.01 probability-of-ignition curve by Lewis and von Elbe.

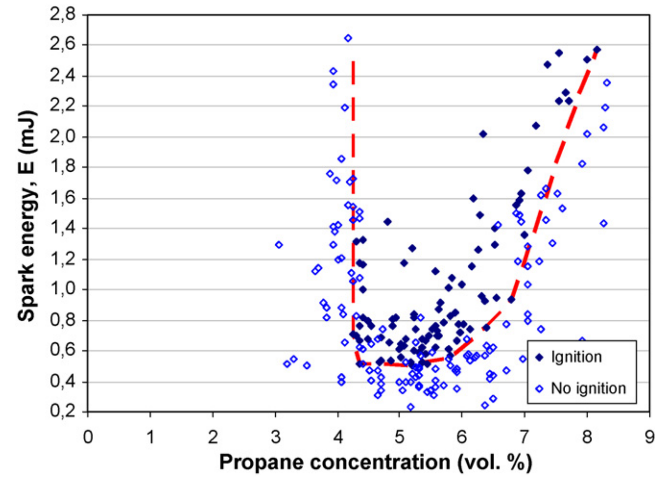

Fig. 5. Minimum electric spark energy for ignition of propane/air mixtures as a function of propane concentration.

The question arose whether the discrepancy between the MIEs of 0.46 and 0.48 mJ found by Moorhouse et al. and in the present work respectively, and the 0.25 mJ by Lewis and von Elbe, could be attributed solely to using different probability-of-ignition levels for defining MIE. In order to answer this question, regression analyses of the data obtained in the present work were performed, first simple linear regression, and then applying the approach of Moffett et al. [8]. They assumed that probability of ignition, $P(E)$, for a given spark energy, E, can be calculated by the following logistic regression equation:

$$P(E) = \frac{1}{1 + e^{-\beta_0 - \beta_1 E}} \tag{4}$$

where β_0 and β_1 are coefficients estimated by maximizing the likelihood function. For a certain probability of ignition $P(E)$, values of spark energy, E, can then be calculated by:

$$E = \left(\ln \frac{P(E)}{1 - P(E)} - \beta_0 \right) / \beta_1 \tag{5}$$

A disadvantage of Eq. (5) is that E cannot be found when $P(E) = 1.0$, because the natural logarithm of 0 is minus infinity. However, the equation applies to values very close to unity. The upper confidence limit (UCL) and lower confidence limit (LCL) for the 95%

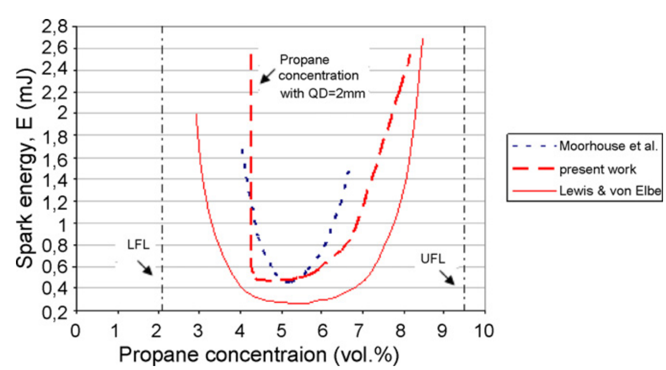

Fig. 6. The minimum ignition energy for propane/air mixtures as a function of propane concentration. The obtained data of ignition energy based on ASTM in compared with the results of Moorhouse et al. [6] and Lewis and von Elbe [1]. The lower and upper flammability limits of 2.1 and 9.5 vol.% respectively are also indicated.

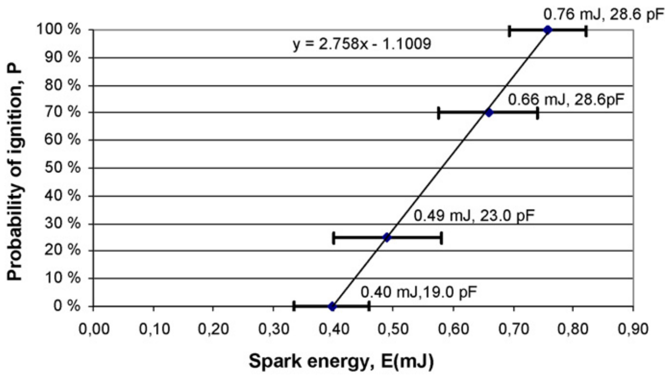

Fig. 7. Linear regression line for the probability of ignition for 5.2 vol.% propane/air as a function of spark energy. The arithmetic mean values of the applied spark energies with bars indicating ±1 standard deviation, and the values of the capacitances used, are also given.

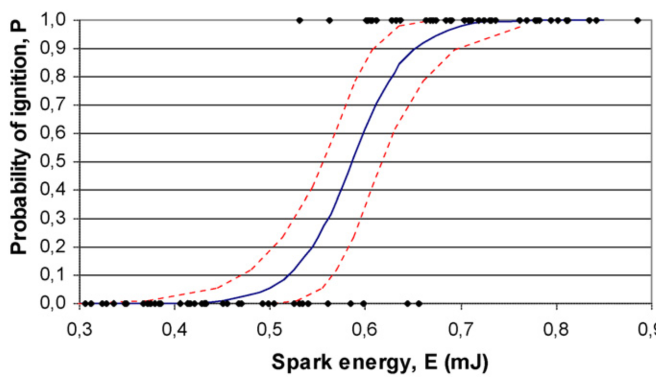

Fig. 8. Logistical probability distribution with 95% confidence envelope for spark ignition of 5.2 vol.% propane/air. The basic experimental data points (ignition or no ignition) of the 80 ignition tests performed as a function of spark energy are also given.

confidence interval for E can be estimated by:

$$\frac{\text{UCL}}{\text{LCL}} = E \pm z_{\alpha/2}\sqrt{\frac{(\sigma_{00} + 2E\sigma_{01} + E^2\sigma_{11})}{\beta_1^2}} \tag{6}$$

Here σ_{00}, σ_{11} are the variances and σ_{01} is the covariance of β_0 and β_1. α for 95% confidence interval is 0.05 hence $z_{\alpha/2}$ is the z value from a standard normal distribution. The covariance of β_0 and β_1, σ_{01} is the product of correlation factor, ρ and standard deviations of β_0 and β_1.

Fig. 7 gives the result obtained using simple linear regression, whereas Fig. 8 gives the result of a regression analysis using the logistical probability distribution described above.

The numerical outcomes of all the analyses are summarized in Table 1. As can be seen, both models give MIEs at a probability of ignition of 0.01 that are significantly higher than the Lewis and von Elbe value of 0.25 mJ. It may seem useful, therefore, to discuss whether the MIE values for gases published by Lewis and von Elbe [1] are unnecessarily conservative.

Table 1
Estimated MIEs for propane/air (5.2 vol.%) for probabilities of ignition of 0.01 and 0.5 using the experimental data obtained in the present work using the ASTM (2009) standard. For the linear regression data the ±number indicates 1 standard deviation, whereas for the logistic regression data it indicates the distance from the central value to the 95% confidence points.

	E calculated by linear regression	*E* calculated by logistic regression
$P = 0.01$	0.40 ± 0.06 (mJ)	0.45 ± 0.08 (mJ)
$P = 0.50$	0.58 ± 0.07 (mJ)	0.59 ± 0.03 (mJ)

5. Conclusions

1. A copy of the standard ASTM [5] electric spark generator was constructed and used to determine MIE of propane/air at normal atmospheric pressure and temperature, following the prescribed procedure of the standard. It appeared, however, that the standard does not prescribe any statistical procedure for deriving the MIE value from the primary test results.
2. We therefore decided to use the procedure of Moorhouse et al. [6]. This gave a MIE for propane in air of 0.48 mJ at a propane concentration of 5.2 vol.%, which is in close agreement with the value 0.46 mJ found by Moorhouse et al., but nearly twice the value 0.25 mJ reported by Lewis and von Elbe [1].
3. By applying both linear and logistic regression analyses to the experimental data obtained for 5.2 vol.%, the two MIEs corresponding to a probability of ignition of 0.01 were calculated, the former being 0.40 mJ and the latter 0.45 mJ. Both values are significantly higher than the value of 0.25 mJ reported by Lewis and von Elbe [1].
4. Our experiments showed that the spark gap of 2.0 mm between the flanged electrodes equals the quenching distance for a propane/air mixture of about 4.2 vol.% on the fuel-lean side, which is in close agreement with Fig. 170 in Lewis and von Elbe [1]. However, on the fuel-rich side we did not find any specific propane concentration at which there was a very sharp rise of the energy required for ignition in the same way as on the lean side. However, according to Fig. 170 in Lewis and von Elbe [1] 2.0 mm would be the quenching distance for 6.3 vol.% propane in air.
5. It may be useful to clarify the statistical criterion by which the MIE data of Lewis and von Elbe [1] were derived, and to discuss whether their data are unnecessarily conservative.
6. The current ASTM [5] test method for determination of MIEs of gases and vapours provides little guidance as to the exact way in which the ignition tests should be performed, and no guidance at all as to the statistical procedure that should be applied for deriving MIE from the raw data. It is suggested that this essential information be added to the text of the standard.

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