Journal of Hazardous Materials, 8 (1984) 271—278
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

THE MAXIMUM EXPERIMENTAL SAFE GAP: COMPARISON OF RESULTS FROM 8-LITRE AND 20-cm^3 EXPLOSION VESSELS

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(Received August 22, 1983; accepted September 30, 1983)

Summary

Maximum Experimental Safe Gap measurements in the 20-cm^3 and 8-l apparatuses are compared for some oxygen-enriched fuel—air mixtures. For a given fuel, a discontinuity in the curves of MESG against nitrogen content is observed in both the 20-cm^3 and the 8-l apparatus results, but occurs at higher nitrogen content in the larger apparatus. Thus with some mixtures, the MESGs measured in the 20-cm^3 apparatus differ considerably from the values measured in the 8-l apparatus.

These differences are qualitatively explained with reference to the changes that occur in the properties of the hot jet ejected through the flame-path as the internal explosion pressure increases.

Introduction

The Maximum Experimental Safe Gap (MESG) is a familiar quantity used in the manufacture of flameproof electrical equipment, and is defined as the maximum distance between parallel surfaces that prevents flame on one side of the flame-path formed by these surfaces from igniting all flammable mixtures of air and the fuel under test on the other side.

The two standard apparatuses used for MESG measurements are the 20-cm^3 apparatus and the United Kingdom 8-l apparatus [1]. Except in a few cases results from these two sets of apparatus are similar when the standard procedures are used. However, when the point of ignition in the internal enclosure of the 8-l apparatus is moved from the side (its standard position) to the centre, large differences are observed between the MESGs measured by these methods.

In a previous study, MESGs have been measured for a series of oxygen-enriched fuel—air mixtures using the 20-cm^3 apparatus. These results have been described by Lunn [2], and an explanation has been given of the discontinuities in the curves of MESG against nitrogen content.

In order to make a systematic comparison of results, the MESGs of a

0304-3894/84/$03.00

series of oxygen-enriched fuel—air mixtures have been measured in the 8-l apparatus to examine the differences which arise and to offer an explanation of them.

Experimental results

Figure 1 shows the results from the 20-cm^3 apparatus and Fig. 2 shows the results obtained for oxygen-enriched methane—air and hydrogen—air mixtures from the 8-l apparatus with side ignition.

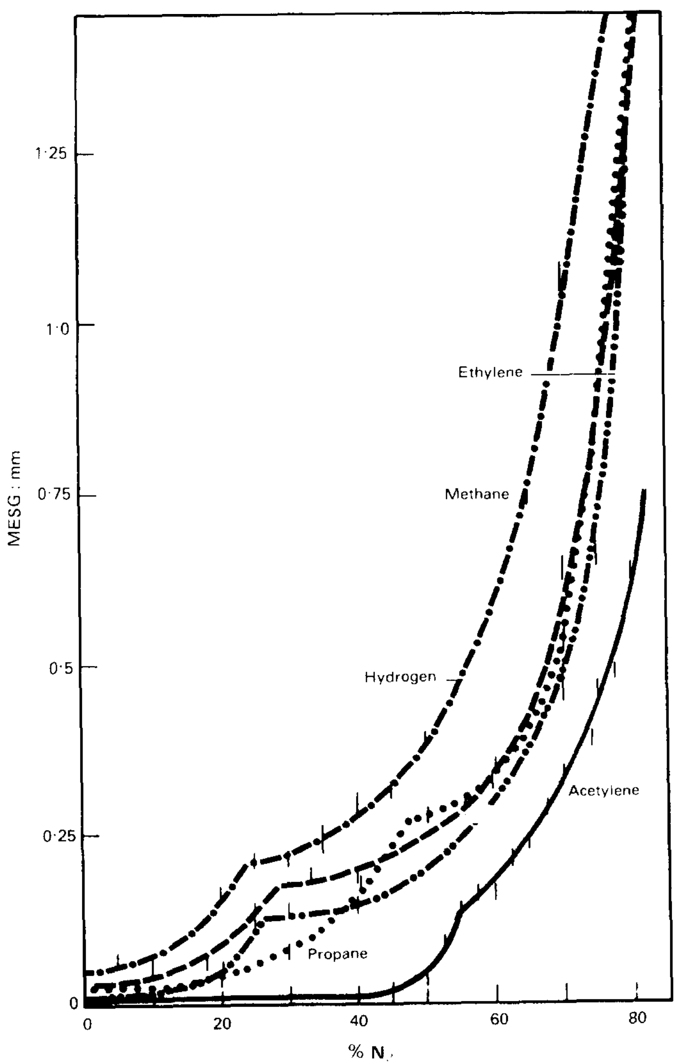

Fig. 1. MESG measurements in the 20-cm^3 apparatus: fuel—oxygen in stoichiometric proportions with added nitrogen.

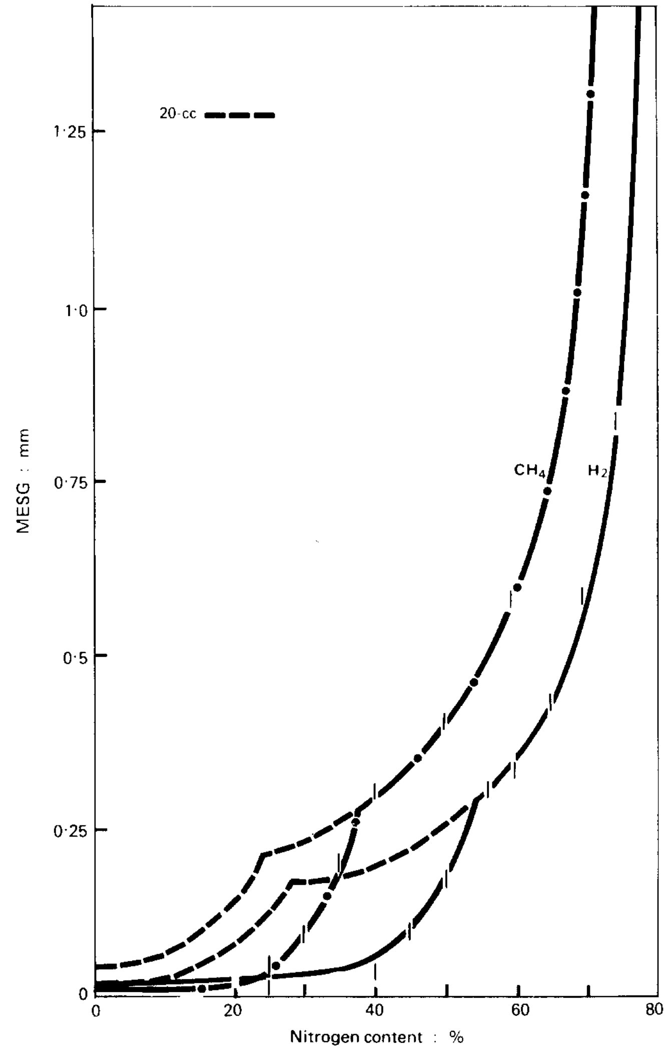

Fig. 2. MESG measurements in the 8-l apparatus: side ignition (fuel—oxygen in stoichiometric proportions with added nitrogen).

Discussion

All the curves of MESG against nitrogen concentration have a similar form. At high nitrogen content high values of MESG occur, and the MESG values from both sets of apparatus are, within experimental error, equal. When the discontinuity in the gradient occurs it does so at a higher nitrogen content in the 8-l apparatus than in the 20-cm^3. As the nitrogen content decreases, the results from the two sets of apparatus diverge, until at very low nitrogen content they again become close.

The most probable explanation of the discontinuity is the onset of sonic flow in the jet of hot gas leaving the flame-path. Sonic flow occurs because, as the gas mixture reactivity rises, increases in the internal explosion pressure result in increases in the velocity of the jet. This description explains why in the 8-l apparatus the discontinuities occur at a less reactive mixture: because of the larger internal volume compared to the safe gap area, higher internal explosion pressures than in the 20-cm^3 vessel should be generated by a given mixture in the 8-l apparatus than in the 20-cm^3 for a given safe gap width.

There are three experimental conditions which can be considered in a discussion of MESGs:

(a) the 8-l apparatus with side ignition,
(b) the 8-l apparatus with central ignition,
(c) the 20-cm^3 apparatus,

with a further subdivision between:

1. a gas mixture of high reactivity,
2. a gas mixture of low reactivity.

In either apparatus and with any combustible gas mixture, as the flame-front moves through the internal enclosure the internal pressure rises, as shown diagrammatically in Fig. 3. The form of the curve in Fig. 3 will remain essentially the same, although factors such as the shape and size of vessel, the aperture dimension, the gas mixture and the point of internal ignition will have quantitative effects. The internal over-pressure causes an outflow of gas through the flame-path. Before the flame reaches the internal edge of the flame-path this gas will be cold, but once flame has reached the internal edge, burnt gas flows through the flame-path and is ejected into the flammable mixture in the external enclosure. It is this initial ejection of hot gas which is important in the following discussion. The critical gap dimension (safe gap) which just prevent ignition of the external mixture by the hot gas jet will be a function of the internal pressure at which the hot gas is ejected. This func-

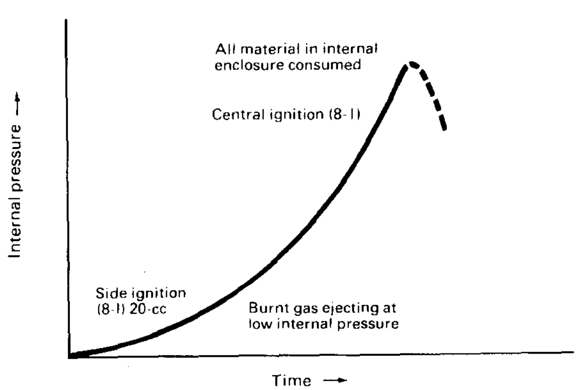

Fig. 3. Diagrammatic representation of rise in internal pressure during an MESG experiment.

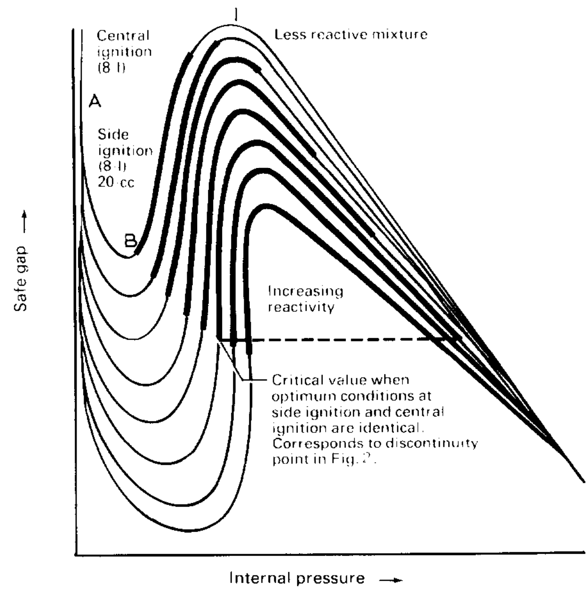

Fig. 4. Diagrammatic representation of variation of safe gap with internal pressure.

tion is demonstrated qualitatively in Fig. 4. In order to simplify the following analysis, the MESG is regarded as the width of the emerging jet of hot gases necessary to cause ignition of the external mixture.

Depending on the ignition point in the internal vessel, the initial ejection of hot gas can occur over a greater or lesser part of the pressure—time curve of Fig. 3 at different points around the circumference of the vessel. Thus in a single MESG experiment there are a range of possible safe gaps corresponding to the range of pressures over which hot gas is ejected, and which follow part of a curve such as curve I in Fig. 4. Thus initial ejection of hot gas need not happen only once in an MESG experiment; it can occur continuously at an increasing pressure as the flame reaches different points of the vessel circumference.

The shape of curve I develops from a consideration of (a) the effects of heat loss from the hot gas as it passes through the flame path, and (b) the properties of the hot jet that determine its ability to ignite the external mixture.

These properties are temperature, which influences through the reaction rate the heating up of the gas jet as it enters the external mixture, and velocity, density and size of the jet (defined by the aperture through which the jet ejects, i.e., the safe gap), which determine the relative rate of entrainment of ambient external mixture into the jet. The relative rate of entrainment is defined as the rate of entrainment relative to the mass of the jet; this influences the cooling of the gas jet. The reactivity of the external gas mixture also influences the rate of reaction, but for a given curve such as curve I in

Fig. 4, this reactivity is constant. Gas flow through the flame-path and entrainment into the jet are complex, but the essential description of the effects is as follows. When hot gas is ejected at low internal pressures (point A in Fig. 4), large critical gaps are obtained, i.e., a wide jet is necessary to obtain ignition of the external flammable mixture. This is because heat losses to the walls become significant for a slow moving gas and a wide jet is necessary to maintain temperature. This is the case despite the fact that the slow moving, low temperature, high density jet will suffer less cooling through entrainment of the external mixture.

As the internal pressure increases (A to B in Fig. 4), so does the hot gas velocity, and ignition can occur when the jet is narrow. Heat loss to the walls is less for a faster moving gas, and therefore a narrow jet can maintain its temperature despite the fact that when the emerging jet is fast moving and has a high temperature and low density, entrainment of cool external gases is increased. Eventually a minimum jet width occurs (point B in Fig. 4). This least safe condition for ignition exists because the temperature increases caused by reduced heat loss to the walls become less as the internal pressure continues to rise while the velocity can continue to increase without restriction. As the internal pressure continues to rise external ignition can be obtained only if the jet is widened. The relative rate of entrainment is decreased by widening the jet and thus the probability of ignition is increased.

The jet width continues to increase until a maximum is reached at an internal pressure at which the flow in the flame-path is sonic. Under-expanded jets are then ejected into the external mixture. Under-expanded jets have a higher density than sub-sonic jets, and as the velocity increases relatively slowly with increases in internal pressure once sonic flow is reached, while the temperature of the jet can continue to rise because of compression effects, external ignition can be obtained with narrow jets giving a high relative rate of entrainment.

If curve I in Fig. 4 is taken to be for a low reactivity mixture, say methane—air, then the results of increasing the reactivity by oxygen-enrichment, or decreasing the nitrogen content, are represented by the series of curves shown. In a practical MESG apparatus the initial ejection of hot gas occurs over part of the pressure range only; this is demonstrated diagrammatically in Fig. 4 by the thickened portions of the curves. These thickened portions represent the behaviour in the 8-l vessel with side ignition, as in this case hot gas ejects, during an internal explosion, over a range of internal pressures. When ignition is central, however, hot gas is initially ejected only once and at one pressure, i.e., the flame reaches the internal edge of the safe gap around the whole circumference at the same time. As gas reactivity increases (i.e., the diluent content decreases), higher internal pressures are reached and thus the range of pressures over which hot gas ejects expands. Similarly, the internal pressure at the very start of ejection of hot gas is likely to rise as the reactivity increases because of the higher expansion ratio resulting from a decreased inert content.

Figure 4 applies to the following six cases:

(a) Low reactivity mixture, 8-l apparatus, side ignition

The hot gas first ejects when the internal pressure is low. Experiments show that for a mixture of low reactivity, such as methane—air, the least safe conditions (smallest MESG) are met at low internal pressures [3] (see Fig. 3), represented by the left-hand side of the thickened curves in Fig. 4. Any hot gas ejecting at higher internal pressures takes no part in determining the value of the MESG because re-ignition has already taken place.

(b) Low reactivity mixture, 8-l apparatus, central ignition

When ignition is central, the initial ejection of hot gas occurs at one internal pressure only, represented by the right-hand side of the thickened curves in Fig. 4. For a low reactivity mixture this is not the least safe condition and safe gaps will be wider than when ignition is at the side.

(c) High reactivity mixture, 8-l apparatus, side ignition

In this case the hot gas ejecting at high internal pressures has a greater probability of causing external ignition than the hot gas ejected at lower pressures. The least safe conditions lie to the right of the maxima in the curves of Fig. 4, on the right-hand side of the thickened portions. As the reactivity increases from low reactivity to high, a point is reached where the least safe conditions are met at both ends of the thickened curves, and when the reactivity increases further, the least safe condition is met at high internal pressures. This switch of the least safe conditions from a low to a high pressure is a probable cause of the discontinuity in the MESG—nitrogen content curves, because the quantitative effects on the MESG of changes in nitrogen content and internal pressure are unlikely to be exactly the same at both sides of the maxima. In the 8-l vessel this discontinuity does not coincide with the onset of the choked flow in the flame-path, but at a higher pressure.

(d) High reactivity mixture, 8-l apparatus, central ignition

Experiment shows that when a mixture is highly reactive, the MESG value for central ignition is equal to that for side ignition. As hot gas ejects at only one pressure represented by the right-hand of the thickened curves, the least safe conditions for both side and central ignition are met at the same high pressure.

As the nitrogen content decreases and the reactivity increases, the trend of the right-hand sides of the thickened portions of the curves in Fig. 4 suggests that any discontinuity in the MESG—nitrogen content curves for central ignition in the 8-l sphere would be expected at very high nitrogen content, and could take the form of a maximum rather than a point of inflection.

(e) Low reactivity mixture, 20-cm³ sphere

Although the ignition point is close to the centre of the internal enclosure, the large exit area of the safe gap compared to the small internal volume means that hot gas first ejects at a low pressure represented by the left-hand side of the thickened curves in Fig. 4. At nitrogen concentrations greater than that at which the discontinuity appears in Figs. 1 and 2, the 20-cm³ measurements are equal to the 8-l side-ignition results. The least safe conditions in the hot jet in the two cases (a) and (e) are both met at low pressures.

(f) High reactivity mixture, 20-cm³ apparatus

Because hot gas ejects over only a short pressure range represented by the left-hand side of the thickened curves in Fig. 4, the onset of choked flow does not take place until the left-hand side reaches the maximum in the curves. The discontinuity in the MESG—nitrogen content curves will consequently coincide with the onset of sonic flow in the flame-path. The discontinuity thus occurs at a much higher reactivity than in the 8-l apparatus. Further, because of the large relative area change across the flame-path channel in the 20-cm³ apparatus, choking probably occurs at the inner edge of the flame-path first, and sonic flow will not be felt at the outlet until higher internal pressures or higher reactivities have been reached. If the 20-cm³ vessel is compared to a converging—diverging nozzle, the hot jet ejecting into the external mixture should not be influenced by sonic flow effects until the "design-condition" is reached.

Conclusions

The experiments and discussion show that at high reactivity, MESG measurements in the 8-l and 20-cm³ apparatuses can differ considerably. The implications for fuel—air MESGs and their application in practice are not serious unless very high internal pressures are reached. Usually, pressures generated by fuel—air explosions will not exceed the values where these MESG differences begin to occur. Only in the case of hydrogen—air is the possibility of unexpectedly low values of MESG in large enclosures a possibility, especially if turbulence promoters are present inside the enclosure.

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