MAXIMUM EXPLOSION PRESSURE IN FLAMEPROOF ENCLOSURES: THE EFFECTS OF THE VESSEL AND THE AMBIENT TEMPERATURE

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Summary

Explosion pressures measured in the Westerberg apparatus for determining the design requirements of flameproof enclosures in various flammable atmospheres (as generally used in the U.S.A.) are not the same as pressures measured in a 4-l, spherical explosion vessel generally used in the U.K. Probable causes of the differences are examined. Explosion pressures can be reduced by heat losses to the outer enclosure, and enhanced by local volumes in which spontaneous ignition may occur, transition to turbulent burning, pressure piling, and transition to detonation, all of which are suspected of influencing the results. As a result of detailed examination of the differences, the application of test procedures for flameproof enclosures can be considered.

Introduction

The two important requirements of "flameproof" electrical equipment for use in flammable atmospheres are: (a) that the equipment must withstand the pressure of an internal explosion, and (b) that the internal explosion must not be transmitted to the external atmosphere.

To determine whether a particular apparatus will withstand an internal explosion, the testing officer explodes a fuel inside the apparatus and records the explosion pressure. He then applies to the apparatus an over-pressure of 1.5 times the maximum recorded pressure. If he is unable to measure the maximum explosion pressure he may use a pressure of 1.0×10^6 Pa for an apparatus of Groups I, IIA and IIB or 1.5×10^6 Pa for an apparatus of Group IIC, in lieu of the pressure estimated from experiment [1].

The problem

In the U.K. the testing officer is free to select the position of the internal ignition and the location of the pressure transducer for his determination of explosion pressure. The fuel he uses for his test is defined [1] and the concentration with air is based on experiments made in about 1940 on explosion pressure in an empty 4-l sphere with central ignition. The results of

those experiments are summarised in BS 229 [2]. The testing officer is expected to smooth out short-duration transients in his determination of pressure; this lack of precision leads to differences in interpretation.

In the U.S.A. testing procedures are based on the experiments of Underwriters' Laboratories of Chicago (UL). The peak pressures were recorded in the Westerberg apparatus, which is the standard apparatus used by UL for the determination of Maximum Experimental Safe Gap (MESG). In some instances the peak pressures were greater than those in the 4-l sphere, and appreciable differences existed among the fuel concentrations required to attain maximum explosion pressure. Some of the UL data were presented to the International Electrotechnical Commission [3—5] and were reported in UL Bulletins of Research [6—8]. As a result, in testing practical apparatus in the U.S.A. the testing officer determines the explosion pressure over a range of fuel concentrations in air.

The peak explosion pressure for methane in the Westerberg apparatus was lower than in the U.K. 4-l sphere (3.4×10^5 Pa compared with 7.0×10^5 Pa), but this increased to 6.9×10^5 Pa when the mixture was agitated. The mixture for maximum explosion pressure was 8.2 per cent in the Westerberg apparatus and 9.8 per cent in the 4-l sphere.

Ignition in the conduit leading to the explosion chamber had little effect on the explosion pressure for methane, but the explosion pressure for acetylene was much greater than the value quoted in BS 229 and reached 7.8×10^6 Pa. No other fuel gave a pressure as high as acetylene, but a number gave pressures significantly higher than those reported in BS 229, e.g., butane, 1.0×10^6 Pa; hydrogen 5.8×10^6 Pa; and ethylene 1.2×10^6 Pa (see Table 2).

TABLE 1

Mixture required to generate the maximum explosion pressure in the spherical vessel (U.K.) and the Westerberg vessel (UL) and the corresponding maximum explosion pressures with a quiescent mixture

	Stoichiometric mixture (%)	Mixture to obtain maximum explosion pressure (%)		Maximum explosion pressure ($\times 10^5$ Pa)	
		U.K.	UL	U.K.	UL
acetylene	7.77	14.50	8.04	10.06	12.41
hydrogen	29.8	32.30	29.10	7.24	9.38
diethyl ether	3.39	4.10	4.00	9.03	7.58
ethylene	6.55	8.00	6.48	8.69	7.58
n-butane	3.14	3.60	3.60	8.41	7.58
methane	9.52	9.8	8.2	7.03	3.45
n-pentane	2.56	3.0	2.54	8.41	4.96
propane	4.04	4.60	4.60	8.41	7.45

This was due in part to pressure waves precompressing some of the mixture before combustion (pressure piling).

When the experiments were repeated in practical flameproof enclosures similar results were recorded. In an enclosure consisting of a rectangular box with a flat lid, ignition at the end of a conduit leading to the box produced a pressure of 1.4×10^6 Pa measured in the middle of the lid. To increase the volume the manufacturer made a domed lid. This small change produced a pressure measurement of 8.1×10^6 Pa.

Table 1 shows some of the differences noted for explosions in quiescent mixtures in the Westerberg apparatus and in BS 229. The differences give standards committees cause for concern, placing in doubt the gas concentrations specified by the IEC [1] for measuring the explosion pressure in an enclosure prior to the over-pressure test. The data are used to support the view that the concentrations specified should be re-examined. Before committees can give reasoned consideration of this request some explanation of the discrepancies in the data is required. This paper records my interpretation of the data.

The apparatus

The apparatus used for the determinations quoted in BS 229 is described by Paton [9]. The vessel was a 4-l sphere, empty except for the spark electrodes, with ignition at the centre. The gas mixture was prepared in a gas holder. After evacuation of the sphere the mixed gas was drawn from the gas holder to prepare for the experiments.

The Westerberg apparatus used by UL was described, but not in detail, in a UL Bulletin of Research [6]. A simplified sketch illustration appears in Fig. 1. The apparatus was a cylinder of 289 mm diameter, 410 mm long and 26.6 l volume. It had a fan at its right hand side, consisting of a circular plate with 24 small blades welded at its periphery. The fan was driven through gearing inside the explosion chamber. Flow from the fan was directed down the wall of the chamber by a cylinder, approximately 215 mm in diameter, suspended inside the chamber by 4 radial spacers.

The receptor vessel was mounted at the left hand side of the chamber. Communication to the receptor vessel was via a 100 mm wide flange gap, which was closed during experiments to measure explosion pressure. The flanges comprised one flange, 19 mm broad, butting against a second flange 25.4 mm broad.

Ignition was by an electric spark, close to the flange gap and the pressure transducer (piezo) was mounted in the vessel wall, close to the receptor. The face of the transducer was covered with black plastic tape to avoid error due to thermal radiation.

On the right hand side of the vessel was a central opening to which was connected a conduit leading, via a valve, to a fan for circulating and mixing the gases. The valve left about 0.23 m of conduit connected to the vessel.
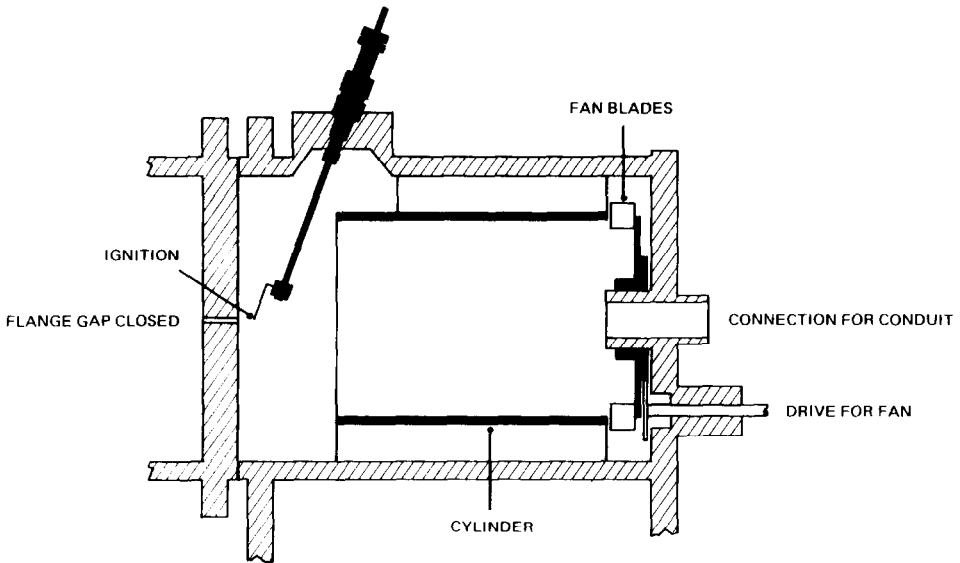
Fig. 1. Explosion chamber of the Westerberg apparatus.

The return for the circulation system was at the side of the vessel, almost in line with the ignition electrodes, with a valve mounted about 0.1 m from the vessel. The conduit appeared to be about 38 mm in diameter.

The vessel was filled by the method of partial pressures. With the valves in the circulating system open, the vessel and pipework were evacuated. Flammable gas was then allowed to enter until the appropriate partial pressure of the gas component of the required mixture was achieved. Pressure was then restored to atmospheric by adding air.

Explosion pressure in a quiescent mixture

Explosion pressures recorded in experiments are never equal to explosion pressures calculated on a simple theoretical basis.

Errors occur through the effects of dissociation, inaccurate knowledge of specific heat and other thermodynamic properties of the burnt gas. Losses occur through quenching of the flame at surfaces and heat losses to surfaces.

Errors in measurement might occur through heat transfer to the gauge (usually avoided by masking the gauge with black tape), or by fluid flow effects causing the gauge to record the kinetic component of stagnation pressure, or reflected pressure if shocks occur. The last two points are real effects and may be reflected in the stress in the chamber casing.

Losses due to heat transfer to the apparatus depend on the temperature difference between flame and surface and the area and duration of contact. The explosion in the 4-l sphere generates its maximum pressure at the same time as the first contact between hot gas and the spherical wall. Therefore,

heat loss is close to minimum and the time taken to achieve maximum pressure is not important for estimating heat loss. The mixture ratios for maximum explosion pressure for the 4-l sphere are richer than stoichiometric, and in most cases burning velocity is less than maximum.

The UL Westerberg apparatus differs in that it contains a cylinder and fan, thus increasing the surface available for heat transfer, and in that ignition is at one end of the vessel, thus increasing the time available for heat transfer. The optimum mixture for maximum explosion pressure is now the mixture that has maximum burning velocity, as this leads to a minimum time of contact between hot gases and surfaces and hence minimum heat loss. The significance of heat losses can be seen best by comparing the data for methane in Table 1; heat losses in the Westerberg apparatus lead to a reduction in maximum explosion pressure from 7.0×10^5 to 3.4×10^5 Pa. The loss for propane and butane is not so great. Normal burning velocity at ambient temperature and pressure is not sufficiently different to account for the variation. However, as pressure increases the burning velocity goes down for methane and goes up for propane. Small differences in burning velocity affect the transition to turbulent burning, especially with the obstructions inside the apparatus, and lead to shorter explosion times for propane and butane. There are insufficient data on the effects of pressure on burning velocity of pentane to allow comparison of the explosion pressure of pentane in the Westerberg apparatus with the pressure of the lower alkanes.

For two mixtures, acetylene and hydrogen with air, explosion pressure is higher in the Westerberg apparatus. These two mixtures have the highest burning velocities of the mixtures considered by UL; hence the losses are lowest. In addition their high burning velocities probably lead to turbulence and flame acceleration as flame negotiates the obstacles of the fan and baffle. This appears to lead to a further reduction in losses, possibly reducing the losses from thermal radiation to below the level in the 4-l sphere. The pressure may also be intensified due to generation of shocks with the application of the reflected shock pressure to the gauge.

Explosion pressure in turbulent mixtures

Two sets of pressure measurements are quoted by the IEC [3] : ignition close to the flange gap and ignition remote from the gap of the Westerberg apparatus. There is little difference between the two sets of data, and only the set of data for ignition close to the flange gap is reproduced here in Table 2.

In general, the pressures are higher than for quiescent mixtures, indicating that higher flame speeds in turbulent flow reduce the time available for heat losses to the apparatus. However, there are a number of anomalies. The increase in the already high flame speeds for acetylene and hydrogen leads to further intensification of the effects of shocks and shock reflections. The pressure of 1.8×10^6 Pa for acetylene is close to the pressure expected for

TABLE 2

UL maximum explosion pressures in quiescent and turbulent mixtures and in a vessel
with connected conduit

	Maximum explosion pressure ($\times$ 10^5 Pa)		
	Quiescent	Turbulent	Conduit
acetylene	12.41	17.88	78.60
hydrogen	9.38	12.96	58.26
diethyl ether	7.58	12.27	13.79
ethylene	7.58	6.76	12.41
gasoline (nahta R)	6.55	10.67	11.03
n-butane	7.58	8.89	10.00
methane	3.45	6.89	5.31
pentane	4.96	6.89	8.62
propane	7.45	6.76	10.20

a detonation, and it appears that local shock compression of a mixture
leads to zones in which spontaneous ignition occurs due to the high tem-
perature.

For turbulent mixtures, gasoline exhibits a higher explosion pressure than
other alkanes. Diethyl ether also has a high explosion pressure with turbu-
lence. One feature common to both gasoline and diethyl ether is their low
spontaneous ignition temperature compared with other compounds in Table
2. Unburnt mixture, subject to only modest local compression by shocks, is
prone to spontaneous ignition. The ability of these mixtures to be ignited
by shock compression is probably marginal and strongly influenced by the
ignition position.

Pressures generated with ignition at the end of a conduit

There are two possible mechanisms for enhancing explosion pressure.

With the conduit, the Westerberg apparatus resembles the apparatus used
by Lee [10] to study the direct initiation of spherical detonation. The criti-
cal diameter of tube for direct initiation of detonation in an acetylene—air
mixture was found by Lee to be about 80 mm. This is larger than the con-
duit in the Westerberg apparatus, but even if a detonation propagating along
the conduit does not become a spherical detonation in the chamber it will
lead to a coupled shock—flame system with a pressure close to that in a de-
tonation wave. The pressures of 7.8×10^6 and 5.8×10^6 Pa for acetylene
and hydrogen are consistent with the pressure behind the reflected wave in
such a system (see Table 2).

For other mixtures the size of pipe for direct initiation of detonation is
much larger and we can safely assume that there will be no such system of
shock and flame. However, the pressure in the chamber can be increased by

the flame propagating along the conduit through the mechanism of "pressure piling". Unburnt gas is expelled ahead of the flame from the conduit into the chamber, so that explosion in the chamber starts with a higher than ambient pressure. This leads to pressures above those obtained by turbulent burning alone.

Methane has the lowest burning velocity of the fuels considered. Cooling of the gases behind the flame in the conduit would reduce the flow of unburnt gases into the chamber and the pressure piling effect is minimal. It is probably for this reason that the pressure for methane is less than that for a simple turbulent mixture.

The pressure for a practical enclosure increased from 1.4×10^6 to 8.1×10^6 Pa by revising the design of the lid; it would appear that the revised lid position coincided with the transition to detonation. The static pressure produced by a detonation is about 1.7×10^6 Pa; higher pressures are recorded when the wave is reflected from a wall, and even higher pressures appear when the wave is just being formed. Small changes in the length of the conduit, its contents and its location in the enclosure should be expected to have a marked influence on explosion pressure as this critical condition is approached.

Implications for the use of flameproof enclosure at low ambient temperature

Two reports [11,12] give evidence for an increase in explosion pressure in laboratory apparatus of between 32 and 40 per cent for a reduction in ambient temperature from 20 to -50 °C.

However, in a private communication, Schram of UL provided evidence for a much larger effect of ambient temperature for practical flameproof equipment in ethane. For a 40 hp motor in ethane he reported an increase in explosion pressure of 100 per cent (from 4.7×10^6 to 9.4×10^6 Pa) for a temperature reduction from 21 to -51°C, but an increase of only 15 per cent (1.8×10^6 to 2.0×10^6 Pa) for a 300 hp motor over a similar range. Over a slightly greater range, 25 to -75°C approximately, Schram reported much larger pressure increases; for a 250 hp motor a 285 per cent increase (4.4×10^5 to 1.7×10^6 Pa) was noted. For a 2.13 m long, 50 mm diameter conduit in an ethylene—air mixture, the maximum pressure at low ambient temperature could not be recorded, being over 2.4×10^6 Pa. At ambient temperature explosion pressure in the same apparatus was 7.8×10^5 Pa.

In general, the fuel—air mixture that achieved maximum explosion pressure was different for each temperature. In tests with cold ethylene—air mixtures in various enclosures the concentrations found to give maximum explosion pressure ranged from 4 to 8.5 per cent.

Two effects appear to influence the UL results. Firstly, the effect of pressure piling is enhanced at low ambient temperature. The enhancement has little effect on the mixture concentrations to achieve maximum pressure, but the pressure is above that predicted by the empty box experiments. Second-

ly, at low temperature the run-up distance for detonation is reduced, and Schram, in some instances, compared explosions at ambient temperature, when detonation cannot be achieved, with explosions at low temperature when the apparatus has a dimension similar to the run-up distance at low temperature. With detonation the maximum pressure is recorded when the detonation is just being formed close to the pressure transducer, and the fuel concentration needs to be adjusted to find this condition.

Conclusions

The maximum explosion pressure and corresponding fuel concentration determined with central ignition in a spherical vessel is a useful combustion measurement in that this is the apparatus that has least effect on the measurement. A sphere comes close to this ideal.

Practical flameproof apparatus may not approximate to this ideal. With rapid flame accelerations and shock effects due to obstacles inside the vessel and due to turbulence, the explosion pressures might be higher than in an empty box, especially if the fuel is very reactive (acetylene, hydrogen) or has a low ignition temperature (diethyl ether, gasoline). On the other hand, thermal losses may reduce the explosion pressure.

Where detonation is likely to affect the maximum explosion pressure the positions for ignition and for the transducer are critical. Small changes in enclosure shape can make a vital change to the measurement of explosion pressure, as also can changes in fuel concentration. The use of a conduit leading directly into an enclosure can affect pressure piling and transition to detonation.

For an empty box a drop in ambient temperature from 20 to $-50°C$ increases the explosion pressure between 32 and 40 per cent.

For practical flameproof enclosures at low temperature, pressure piling and detonation effects can be severe and have caused increases in explosion pressure very much greater than 40 per cent for the same temperature range.

The pressures recorded that were above about 1.5×10^6 Pa were probably transient of very short duration, acting over only a part of the internal surface of the enclosure. There was no indication in the experiments how the stress in the enclosure casing would respond to short-duration transient pressures.

From the experiments reported it is clear that the explosion pressure determined in industrial enclosures is not simply related to the pressures recorded in a spherical test apparatus. The influence of turbulence, heat losses, pressure piling, shock reflections and detonation are important, but not easy to predict. Pressure is sensitive to small variations in apparatus design, stoichiometry, ignition position and pressure transducer position. These factors should be remembered when designing a test for the determination of explosion pressure in flameproof electrical equipment.

Acknowledgement

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