Characterisation of confined turbulent gas explosions with reference to protection methodologies

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Introduction

Current NFPA (NFPA 68,1998) guidance for the design of deflagration vents for gas explosions include correlations based on the deflagration index , K_g, (in theory independent of the vessel volume) defined by

$$K_g = (dP/dt)_{max} \cdot V^{1/3} \qquad (1)$$

where, $(dP/dt)_{max}$ is maximum rate of pressure rise measured in a in a totally enclosed compact vessel of volume V with an initially quiescent gas-air mixture. The application of the empirical equations recommended by NFPA 68 is limited to zero turbulence conditions. They do not apply for a gas system that is initially turbulent or where turbulence might be generated by interaction of the explosion induced flow with obstacles (e.g. equipment) inside the protected vessel. The NFPA guide recommends that the hydrogen Kg (550 barm/s) should be used for venting initially turbulent gases that have maximum rates of pressure rise values, in the quiescent state, that are close to or less than that of propane. Additionally, correction factors are introduced to compensate for the fact that Kg is not really independent of the volume of the vessel but it increases with vessel volume. This is related to various flame self-acceleration effects such as flame surface cellularity resulting in increased burning rates due to an increase in flame surface area. This effect would be expected to be of importance when initially quiescent $1 m^3$ (or smaller volume) test results are applied to typical industrial plant with volumes of the order 10-10000 m^3

A similar explosion index, K_{st}, is used for standardised dust-air explosion characterisation (ISO 6184/1, 1985). In order to produce a well dispersed flammable dust cloud in a given test vessel, pressurised injection of a dust sample is used. This results in a turbulent dust-air mixture and the delay time between initiation of dust dispersion and ignition has a strong influence on the effective turbulence levels. It is generally assumed that K_{st} values are independent of vessel volume. This might be justified by the overriding effect of initial turbulence on explosion development compared to flame self-acceleration effects that are important for initially quiescent mixtures. The measurement of K_{st} values, under conditions of turbulence that reflect those in industrial plant, allow a degree of confidence in their application to realistic processes. Conversely, K_g values measured for quiescent gas-air mixtures might negate their application to industrial enclosures where there might be initial flow conditions and/or turbulence generating obstructions, in the form of inherent process equipment. Even if zero initial turbulence conditions could be assumed, the influence of flame self-acceleration effects and the interaction of explosion induced flow with the enclosure and its contents would then become important as K_g values would increase (compared to those measured under standard conditions).

In this study we report explosion experiments under different turbulence conditions in a standard ISO $1 m^3$ vessel, for different gas-air mixtures. The measured flame speeds and Kg values are correlated to the levels of turbulence derived from published turbulence decay models for identical vessels.

Experimental

Gas-air mixtures were exploded in a 1.138 m^3 closed cylindrical steel vessel, with a length to diameter ratio of unity. The vessel was constructed to the specifications of the ISO 6184/1 (1985) standard for the determination of explosion indices of dusts and gases. The mixtures were centrally spark ignited by a capacitor discharge energy of 16 J. Mixtures were prepared using partial pressures by evacuating the vessel to less than 20 mbara followed by injection of the required volume of fuel gas. The vessel pressure was then increased to 923 mbara by injection of ambient air. The pre-ignition turbulence level was controlled by the delay time, t_d, between introduction of air from a 4.5 litre external chamber, connected to a perforated C-ring inside the vessel, via a fast acting pneumatic ball valve, and ignition. The external chamber was pressurised to 20 barg with air. Operation of the ball valve resulted in an increase in vessel pressure by 90 mbar, giving a total nominal pressure prior to ignition of 1013 mbara (1 atm). This rapid injection of air aided mixing of the fuel gas with air. For initially quiescent explosions, the external chamber was not used and the mixture was made up in the vessel with a pre-ignition pressure of 1 atm.

Explosion pressure histories were monitored using a piezoresistive pressure transducer mounted in the wall of the vessel. An array of 13 type-K mineral insulated, exposed junction thermocouples were positioned along the horizontal axial centreline of the vessel. A similar array of 9 thermocouples was positioned along the vertical radial centreline. The thermocouples were used to detect the time of flame arrival and thus enabled calculation of flame speeds. The sampling rate used by the data acquisition system was 5000 samples/s. Subsequent signal conditioning and analysis was carried out using specialist software.

The rate of pressure rise was calculated by differentiation of a section of the pressure signal after elimination of electronic noise, by a degree of smoothing. Methane (10%), ethylene (7.5%) and hydrogen (40%) (v/v) mixtures with air, were tested under quiescent and turbulent conditions of variable rms turbulent velocity, which was controlled by the ignition delay time after injection. The turbulence levels were quantified from published measurements in identical vessels and these were correlated to measurements of flame speeds, Kg values and estimates of the turbulent burning velocity.

Influence of ignition delay time

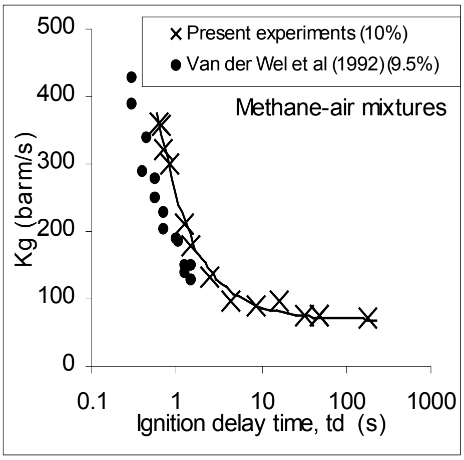

Fig. 1

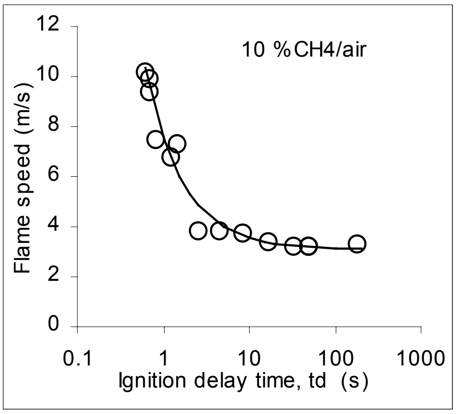

Fig. 2

K_g values as function of ignition time delay

The maximum rate of pressure rise, expressed as a K_g value using Eq. 1, is plotted as a function of ignition delay, t_d in Fig. 1 for 10% methane-air mixture tests. The data shows a decrease in K_g as t_d is increased. K_g remains essentially constant at about 69 barm/s after a t_d of the order of 30 s. This suggests that at this time turbulence had dissipated to essentially quiescent conditions (measured Kg of 67 barm/s). Also shown on Fig. 1 is data from Van der Wel et al (1992) for stoichiometric mixtures using short time delays, in a similar ISO-designed 1m^3 vessel (low energy ignition source).

Flame speeds

For explosion suppression systems, the flame speed can be used to estimate the diameter of an incipient explosion at the time of suppressant interaction with the flame. This provides information for design of suppressant and hardware requirements. There is limited turbulent flame speed data in the literature.

In the present experiments, for each ignition delay, the flame speed was roughly constant between 0.2 and 0.7 of the radius from the spark. This range was used to include a sufficient number of data points without the complication of early explosion development when the flame might not be fully influenced by turbulence, and mixture pre-compression effects when the flame was close to the vessel wall. A linear curve was fitted to the distance-time data for this range. The gradient of the curve then represented the flame speed. Fig. 2 shows the flame speed, S_f, calculated using this gradient method, plotted as a function of delay time, t_d for the methane-air mixtures. For ignition delays above 30 s the flame speed decreased to about 3 m/s which compares well to the value of 2.8 m/s measured for an initially quiescent methane-air mixture.

Published turbulence measurements

The fundamental influence of turbulence on combustion development has been investigated in constant volume chambers by a number of researchers. Application of the understanding gained from turbulent combustion research, to explosion protection systems currently requires the explicit dependence of standardised design parameters such as K_g and flame speed on the turbulence levels which may be encountered by a propagating flame under normal process/system operating conditions. Recent experimental studies (in similar test vessels to that reported in this paper) investigating the influence of turbulence on these parameters, have been reported by Scheuermann (1994), Tamanini and Chaffee (1990) van der Wel et al (1992) and Tai and Kauffman (?). Different methods of turbulence generation have been employed, including perforated semicircular tube (C-ring) dispersion systems (the technique specified by ISO 6184/1, 1985) and discharge from opposing nozzles. These systems are characterised by an initial rapid increase to peak values of rms turbulence velocity, u', after the onset of turbulence generation, followed by a longer period of turbulence decay. The magnitude of u' is specific to the method of injection employed and the spatial resolution of the measurements.

Scheuermann (1994) reported average values of u', derived from LDA measurements of the vertical and horizontal components of u' for a 1m^3 ISO test vessel, using C-ring dispersion. The measurements were carried out in three measurement planes with 23 positions in each plane across the vessel radius, providing a fairly comprehensive spatial coverage of the test volume. He reported averaged values decaying with time, t, according to,

$$u' = 1.6944\left(1 - e^{-0.1135/t}\right) \qquad (2)$$

This equation applies to the turbulence decay period, taken as 300ms after the onset of turbulence generation and is shown in Fig. 3.

Hauert and Vogl (1995) also reported LDA measurements of u' in a $1m^3$ ISO vessel with C-ring dispersion. The measuring probes were located at the centre of the vessel. Five independent single measurements were averaged over an empirically determined time interval. The correlation for the horizontal component of u' was given as,

$$u' = 11.42e^{-4.8t} + 0.56 \qquad (3)$$

and the vertical component of u' as

$$u' = 62\,e^{-5.9t} + 0.85\ . \qquad (4)$$

The outputs form these correlations were averaged and the result is shown in Fig. 3. Both the individual component correlations and the combined average gave a constant u' after about 1.5 s. The present experiments involved a range of ignition time delays of 0.6 – 180 s. In order to apply these correlations it was necessary to formulate a suitable decay expression applicable to long time delays (low u'). Equation 5 was fitted to the combined average of Eqs. 4 and 5,

$$u' = \frac{0.0598}{1 - 1.0133e^{-0.0702t}} \qquad (5)$$

(its plot is shown in Fig.3 – dashed line) representing an average value of the turbulence level at the vessel centre. By contrast Eq. 2 represents spatially averaged u' values that are effectively vessel volume averaged values. Fig. 3 shows that for the same value of time, t, Eq. 2 gives average u' values that are significantly lower than those of Eq. 5. As both Eqs. 3 and 5 were derived from measurements in identical vessels, these results strongly suggest turbulence generated by C-ring injection in a standard ISO test vessel is non-homogeneous.

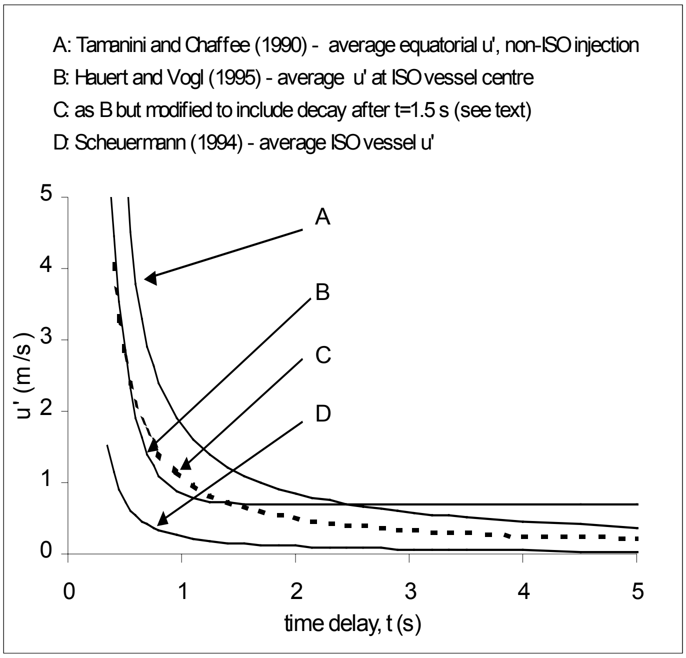

Fig. 3

Also shown on Fig. 3 are the turbulence levels reported by Tamanini and Chaffee (1990) in a 1.35 m^3 spherical vessel using a high pressure air injection system from two opposing 35 litre chambers, via hemispherical perforated nozzles. Transient turbulence levels were determined using a bi-directional impact velocity probe. Measurements from three different locations (0.25, 0.5 and 0.75 radii) on an equatorial plane vertical to the plane of injection were averaged and the variation of u' with time was expressed as,

$$u' = 1.286(t - 0.34)^{-0.803} \qquad (6)$$

It should be noted that the authors reported that on the measurement plane u' was essentially uniform. For the range of t_d values shown in Fig. 3, calculated values for u' using Eq.6 were found to be higher than those calculated using Eqs. 2 and 5 which were based on measurements in ISO-designed vessels, as described above. Equation (6) is specific to the method of turbulence generation employed (not usable in estimating turbulence in an ISO standard vessel).

No measurements of turbulence levels were made in the experiments reported in this paper. Instead, the turbulence decay equations discussed above (for an ISO vessel – Eqs. 2 and 5) have been applied, as the test vessel and turbulence generation method used in this study are the same as those used to derive Eqs. 2 and 5.

Determination of burning velocity as a function of u'

The burning velocity, S, was quantified from pressure-time and flame travel distance-time measurements.

The pressure-time method was based on a procedure described by Harris (1983) for the combustion of an initially quiescent gas/air mixture in a totally confined vessel. Assuming combustion takes place in a spherical flame-front of negligible thickness that delineates the burnt and unburnt gases which obey the perfect gas law, the burnt gases attain equilibrium within negligible time, pressure is uniform throughout the vessel and pressure is nearly constant, it can be shown that an approximate solution of the relevant equations gives,

$$\Delta P = \frac{4\pi}{3V} P_0 E^2 (E-1)(S \cdot \Delta t)^3 \qquad (7)$$

Where ΔP is a small pressure rise occurring in a small time interval Δt, P_0 is the initial pressure E is the mixture expansion factor, S is the burning velocity and V is the volume of the vessel. The assumption of nearly constant pressure can only be valid in the very early stages of the explosion, and consequently the validity of Eq. 7 is limited to this period.

In a practical closed vessel experiment the expansion factor can be taken as equal to the ratio of the maximum pressure to the initial pressure ($E=P_m/P_o$), both of which can be measured. This definition of E also accounts for any deviations from adiabaticity. Equation 7 can then be used to derive a value of the burning velocity S in the early stages of the explosion. Tamanini and Chaffee (1990) measured the time Δt for a rise of pressure ΔP of 0.5 bar above P_o, and hence determined S using Eq. 7. The same technique was used in this work as one way of deriving S and the results are shown in Fig. 4, where the burning velocity is plotted against u' estimated from Eqs. 2 and 5 (vessel average and central region respectively).

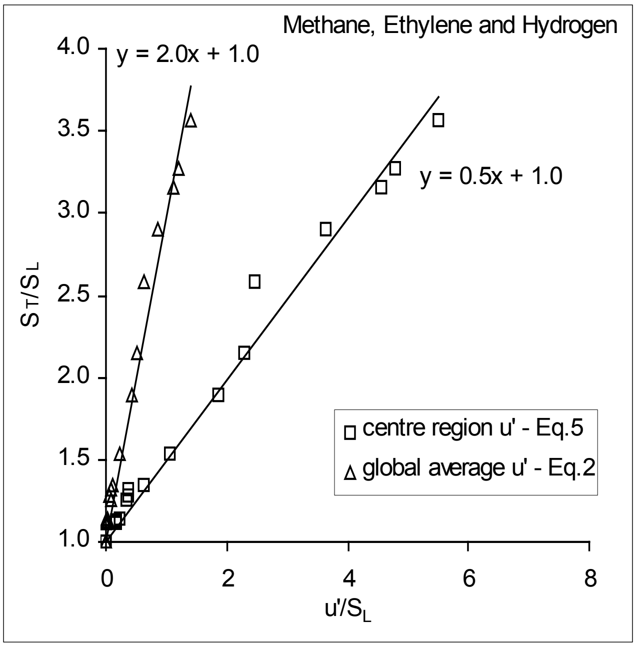

Fig. 4

The data in Fig. 4 cover 14 turbulent tests for methane (10%), 2 hydrogen (40%), and 1 ethylene (7.5%) plus a single laminar test for each mixture. Both the laminar (S_L) and turbulent (S_T) burning velocities were determined by solving Eq. 7 for S. The laminar values thus determined were 0.37 m/s for methane, 0.85 m/s for ethylene and 3.6 m/s for hydrogen. These match typical literature values for these gas-air mixtures, which provides some validation of the pressure-time technique. The burning velocities were also determined in a more direct fashion from the flame speed measurements (averaged between 20 to 70% of the vessel radius) and divided by the expansion factor. The values thus determined were in good agreement with those derived from the pressure-time technique providing further confirmation of the validity of the technique.

Figure 4 shows a linear dependence of the turbulent burning velocity on u'. However the proportionality constant is significantly influenced by the u' correlation used: The vessel averaged u' results give a constant of 2 whereas the centrally measured u' results give a constant of 0.5. Tamanini and Chaffee (1990), using Eq. 6 which is based on measurements in an equatorial plane, report a constant of 0.53 from their work.

The pressure-time method used to derive burning velocities, (both in this work and in Tamanini's) was based on a pressure rise of 0.5 bar. It can be shown that this pressure corresponds to a flame radius of the order of 80% of the vessel radius. As discussed earlier, the low vessel-averaged u' values reported by Scheuermann compared with much higher central region measurements reported by Hauert and Vogl (1995) suggest non uniformity of turbulence throughout the ISO vessel with low turbulence levels near the walls.

There are several turbulent combustion correlations in the literature of the form shown in Fig.4, and the reported value of the proportionality constant is widely varied. Phylaktou et al (1992) reviewed some of the published data and correlations of this form and showed that there is a significant body of data and theoretical analysis to support a constant of around 2. This would be in agreement with the correlation of the present data using global average u' values as shown in Fig.4.

K_g dependence on u'

In theory quantification of the dependence of Kg on the turbulence levels could have a direct application in allowing a more confident use of turbulent Kg values in gas explosion protection. The Kg values as measured at different ignition delay times were normalised by dividing with the laminar value (67, 289 and 693 barm/s for methane, ethylene and hydrogen respectively) and are shown in Fig. 5 as a function of the dimensionless u' calculated using both Eqs. 2 and 5. As in the case of the burning velocity, a linear dependence on u' is clearly indicated and the non-dimensionalising on both axes brings all three gases on the same line. However, again, the proportionality constant is uncertain as it strongly depends on what is assumed to be the effective turbulence intensity; a vessel average or a centre maximum?

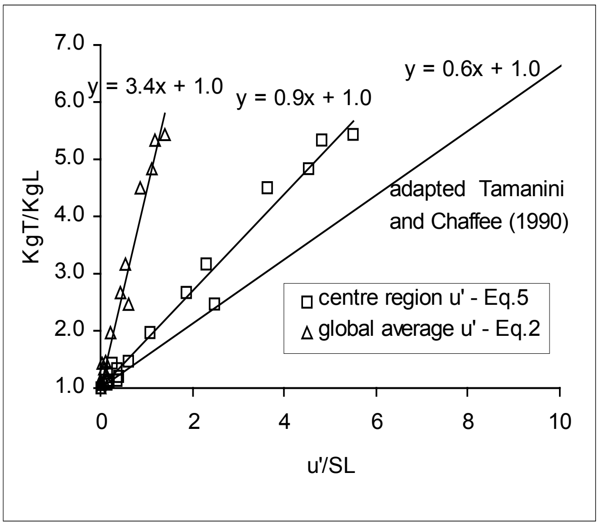

Fig. 5

Tamanini and Chaffee (1990) also reported a linear dependence of Kg on u' for 9.5% methane, 4.0 and 4.8% propane in air. Their correlation for methane was adapted in terms of the parameters of Fig. 5, where it is shown for comparison with the measurements from this lab. The proportionality constant for methane was 0.6 while for the propane mixtures (not shown) the constant was determined to be 0.8 and 1.1 respectively. These values are comparable to the proportionality constant for the present data using the centre region turbulence levels. However, if the vessel average turbulence levels are used a much higher constant of 3.4 is shown.

The data presented in Fig. 5 is useful in that it confirms a linear dependence of Kg on u' and it also gives a range of values that may be used to get an indication of a quantified relationship. This range is however, too wide and it arises from the difficulty in establishing what the relevant levels of turbulence are. The fact that the Kg value is based on the maximum rate of pressure rise (Eq. 1) which is invariably achieved at the very last stages of the explosion development, i.e. just before the flame reaches the vessel walls, makes it difficult to argue that the effective turbulence levels are those measured in the central region. It is likely that there is a fairly repeatable constant profile of spatial distribution of the turbulence intensity within the ISO standard vessel and this would explain the good correlations obtained regardless of whether we used the central-region u' or the vessel-average u', i.e. equally good correlations of the explosion indices could be derived with the turbulence levels at any position within the ISO vessel.

This means that the correlations reported here and in the literature may not be applicable, in a quantitative sense, to any other system. In order to be able to take this information and correctly apply it to the protection design of practical systems we need to be able to relate the explosion enhancement factor to the causal turbulence levels. A possible methodology for achieving this, in the ISO vessel, is currently being investigated at Leeds.

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