Modelling of Methane Explosions and Fault Arcing in Flameproof Mining Enclosures

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A model is described that facilitates calculation of pressure rise due to internal fault arcing in flameproof enclosures of the type used in underground coal mines. In the model arc energy is assumed to heat the gas in the flameproof enclosure, the only energy loss from the gas being by mass loss through flamepaths around the enclosure lids. Calculations are compared with measurements made with flameproof equipment, and the effect of initial flamepath width on pressure rise is established.

Keywords: Fault Arcs, Mining Flameproof Equipment, Pressure Rise

1. Introduction

High power electrical equipment that is operated in hazardous areas in underground coal mines is often contained within "flameproof" enclosures. Such enclosures are thick-steel-walled boxes that are designed to withstand internal ignition of explosive gas mixtures (such as methane and air) that could be caused by sparks due to operation of electrical switchgear. Flameproof enclosures are usually not gas tight. Typically there are mating flat surfaces between the edges of thick steel lids of the enclosures and the sides of the enclosure. Lids are connected to the enclosure by bolts at regular intervals around the periphery of the lid as shown in Figure 1. Hot gases produced by internal gas explosions can escape to atmosphere between the mating surfaces, the path between which is called the "flamepath". The function of the flamepath is to reduce the energy density of gas emerging to atmosphere to below a value that will cause ignition of an external explosive gas mixture.

Fig. 1. A flameproof enclosure

Efficacy of the flameproof enclosure is verified by type tests, involving deliberately-ignited gas explosions within flameproof equipment that is situated in an explosive gas mixture.

The authors have demonstrated, however, that arcing faults within flameproof enclosures containing 3.3 kV and 6.6 kV equipment can cause external ignition of flameproof equipment that is tested to current standards. Small enclosures in which the arc energy density is high are particularly at risk. It is desirable, therefore, that the levels of arc energy density that can be safely withstood by flameproof equipment be identified. As part of such work it is desirable that a method of predicting the pressure rises in flameproof equipment due to fault arcing be established. This paper presents a tentative model that successfully simulates some of the phenomena observed in practice.

2. Methane Explosions

In coal mines explosions occur due to ignition of mixtures of air and methane, and it is generally accepted that maximum pressure rise is produced by ignition of a stoichiometric mixture comprising 9.8% methane (by volume) and air. It is of interest to ascertain the pressure rise due to the explosion of a gas mixture for comparison with the pressure rise due to arcing faults. The equation of the main chemical reaction during a gas explosion is:

$$7.52N_2 + CH_4 + 2O_2 \rightarrow 7.52N_2 + CO_2 + 2H_2O + ENERGY$$ (1)

The ratio of 7.52 moles of nitrogen to one mole of methane occurs in a stoichiometric air/methane mixture, the nitrogen term being included in Equation (1) because of its contribution to changes in system entropy and enthalpy. The net excess energy goes into heating the gas inside the flameproof enclosure.

For a constant volume enclosure it can be shown that the change in pressure due to an explosion is given by:

$$\Delta P = \frac{\Delta H - T_s \Delta S}{V}$$ (2)

Where $P$ is pressure, $\Delta H$ is change in enthalpy, $\Delta S$ is change in entropy, and $T_s$ is temperature.
The changes in enthalpy and entropy between the initial state of the gas before the explosion and the final state after the explosion were calculated following the method of Crowl\(^\text{[5]}\). A solution for pressure rise was found by an iterative procedure in which the initial pressure rise was estimated (guessed), the changes in entropy and enthalpy calculated based on the initial guess, and the pressure rise calculated by Equation (2). If the initial and calculated pressures were different from one another a new initial value was chosen and the process repeated until the values converged.

It was shown that for ignition of a stoichiometric air/methane mixture the pressure rise is 680 kPa and that this is independent of enclosure volume. This is confirmed by the observations of Bradley and Mitcheson\(^\text{[6]}\).

3. Fault Arcing in Flameproof Enclosures

3.1 Arc Energy

All arc faults simulated were three-phase faults with no neutral current as mining power systems have high-impedance grounding. The arc is assumed to be physically symmetrical between phases and the voltage across each phase of the arc is taken as being a square wave with the same period (\(t_{\text{ cyc}}\)) as the power-frequency fault current in the same phase. The internal impedance of a 3.3 kV mine power supply that has a three-phase fault level of 9 kA is about 0.1 ohms, whereas the impedance of a 100 mm, 9 kA arc is about 0.02 ohms. As the fault current is not affected appreciably by the arc impedance, the energy in the red phase is:

\[
Q_r = \frac{4nV_pI_m}{\omega} + V_pI_m\int_0^{t_{\text{ cyc}}/2} |\sin \omega t| \, dt \tag{3}
\]

Where \(n\) is the maximum number of integral cycles of arcing completed, \(V_p\) is the constant arc phase voltage, \(I_m\) is the maximum value of the sinusoidal arc current, \(\omega = 2\pi f\). The total arcing time is given by: \(T = nt_{\text{ cyc}} + t_i\).

Similar equations can be written for the other two phases. Giving a total arc energy of:

\[
Q_{\text{ arc}} = \frac{12nV_pI_m}{\omega} + V_pI_m\int_0^{t_{\text{ cyc}}/2} (|\sin \omega t| + \left| \sin \left( \omega - \frac{2}{3}\pi \right) \right| + \left| \sin \left( \omega + \frac{2}{3}\pi \right) \right|) \tag{4}
\]

Previous studies (e.g. Ref. (7)) have shown that the electric field strength, \(E_{\text{ arc}}\), of a high current arc in air at atmospheric pressure lies between 12 and 20 V cm\(^{-1}\), the precise value depending upon the actual value of arc current. There is also a higher arc potential gradient close to the cathode. For the electrode spacings (typically 70 mm) and arc current considered in this work (9 kA) it was considered appropriate to take the arc potential gradient as being 17 V cm\(^{-1}\). In experiments\(^\text{[3]}\) the arc was constrained by a hook-shaped electrode that was designed to prevent arc movement. Photographic observation of the arc on these electrodes indicated that there was some slight bowing of the arc and it is estimated that the total arc length was \(k\) (approx. 1.4 to 1.8) times the electrode separation, \(l_{\text{sep}}\). In calculations the arc length (\(kl_{\text{ sep}}\)) was taken as being 119 mm (\(k = 1.8\)) because this value gave calculated pressures that were closest to measured values. This arc length also seems reasonable on the basis of photographic observations. If electrodes of any other configuration are used, for example parallel conductors, magnetic effects will cause lengthening of the arc: under this condition the authors have observed that \(k\) can be up to 4.0. Since the phase voltages were approximately square waves then the magnitude of the line voltage is approximately equal to twice the magnitude of the phase voltage and:

\[
V_p = 0.5E_{\text{ arc}}kl_{\text{ sep}} \tag{5}
\]

If arc duration, \(T\), is equal to an integral number of cycles then:

\[
Q_{\text{ arc}} = \frac{3\sqrt{2}}{\pi}E_{\text{ arc}}kI_{\text{ rm}}Tl_{\text{ sep}} \tag{6}
\]

where \(I_{\text{ rm}}\) is the r.m.s. value of current.

3.2 Pressure Rise Due to Internal Arcing

Internal arcing within a flameproof enclosure will heat the air within the enclosure and produce a consequential rise in internal pressure. Bursting of small volume enclosures has been observed\(^\text{[3]}\) due to internal arcing, and high pressure rise can cause loss of flame containment in larger enclosures. Ideally if all incremental energy, \(\delta Q_{\text{ arc}}\), produced by the arc goes into heating the mass, \(m\), of gas within the enclosure then the corresponding temperature rise, \(\delta T\), may be calculated from equation (7) in which \(C_v\) is the constant-volume specific heat of air in the enclosure.

\[
\delta Q = mC_v\delta T \tag{7}
\]

In practice some of the energy will be used to heat electrodes, some may heat the walls and some may escape from the enclosure via the flamepath. Strachan\(^\text{[8]}\) suggested that radiation losses are an important component of the total loss from the arc and that this may increase with duration of the discharge due to electrode evaporation. In arcing experiments made by the authors it was found that after arcing the enclosures were full of a dense brown gas that possibly contained electrode vapour. The capacity of this gas to transmit radiation was not known. Measurements of enclosure wall temperature after arcing, however, indicated that they had not absorbed a significant proportion of the total available arc energy. In modelling it was assumed that arc energy absorbed by the enclosure walls was a very small fraction of the total arc energy, and that no energy is absorbed by the electrodes. The energy escaping via the flamepath is examined in the next section.

4. Expulsion of Material During Arcing

4.1 Energy Loss from the Flamepath

Flameproof enclosures are not designed to be air-tight, but are designed so that pressure relief can occur by expulsion of hot gases through the flamepath. When an internal pressure rise occurs in an enclosure the width of the flamepath may be
increased due to elongation of bolts under tension, and flexing of the lids. In a simple model of the processes in the flamepath proposed in this paper flexing of enclosure lids is ignored, but bolt elongation is included. The main features of the flamepath are shown in Figure 2, in which the width of the flame path, \( x_{\text{gap}} \), and length of securing bolts, \( l_b \), are indicated.

If the initial gap width with no internal pressure rise is \( x_0 \), then the increased width with an internal pressure rise, \( P \), is given by:

\[
x_{\text{gap}} = x_0 + x
\]  

(8)

Where \( x \) is the bolt elongation calculated from \( x = \epsilon l_b \) where \( \epsilon \) is bolt strain, which is evaluated as \( \epsilon = \frac{\sigma}{E} \). Where \( \sigma \) is bolt stress and \( E \) is Young's modulus (205 GPa for steel).

The stress is calculated from the total force on the enclosure lid by assuming that the force is distributed evenly between the bolts securing the lid. The flamepath gap width is then calculated as:

\[
x_{\text{gap}} = x_0 + \frac{P A_i}{E n_b A_b}
\]  

(9)

In Equation (9) \( P \) is the internal pressure rise, \( A_i \) is the lid area, \( n_b \) is the number of bolts securing the lid, and \( A_b \) is the stress area of the bolt.

Increase in pressure within the flameproof enclosure forces hot gas out of the enclosure via the flamepath. Consequently not all energy that is transferred from the arc to the gas within the enclosure remains inside the enclosure, as some heat energy flows out of the flamepath in the form of heated gas. In a increment of time, \( \delta t \), the energy flowing to atmosphere, \( \delta Q \), via the flamepath is given by:

\[
\delta Q = \delta m C_p (T_g - T_{\text{atm}})
\]  

(10)

Where \( \delta m \) is the mass of gas escaping in time, \( \delta t \), \( C_p \) is specific heat of the gas in the flamepath, \( T_g \), is the temperature of the gas in the enclosure, and \( T_{\text{atm}} \) is external gas temperature - taken as 298K in these calculations.

The mass flow rate is given by the expression:

\[
\delta m = UA_{\text{gap}} \rho_g \delta t
\]  

(11)

Where \( U \) is the velocity of gas flow through the flamepath, \( A_{\text{gap}} \) is the cross-sectional area of the flamepath which is equal to \( x_{\text{gap}} \times y_{\text{gap}} \), where \( y_{\text{gap}} \) is the perimeter of the flamepath lid. \( \rho_g \) is the density of gas flowing through the flamepath which in these studies was taken as equal to that of the gas inside the enclosure.

The velocity of gas flow through the flamepath was calculated using equations for compressive isentropic, adiabatic flow through a nozzle, following the procedure of Van Wylen and Sonntag. In the calculations stagnation properties of the gas in the gap were taken as being the corresponding properties of the gas within the enclosure. In practice flow is not isentropic because of friction between the gas and the surfaces of the flamepath, and the flow velocity will be less than predicted by an isentropic model. To allow for this the velocity was multiplied by a Nozzle Discharge Coefficient which is a function of nozzle geometry, Reynolds number, and Mach number. In this application a value of 0.82 was used which is recommended for conditions where the length of the exit path (flamepath length) is more than three times the diameter of the flamepath width.

4.2. Method of Pressure Rise Calculation

The calculation of pressure rise due to internal arcing is done in small time steps. At each time step the following calculations are made:

- gas constants appropriate to the gas temperature are calculated from tables of gas properties,
- arc power and incremental arc energy for the time step are calculated,
- flamepath gap width is calculated,
- rate of mass loss from the flamepath is estimated using the compressive flow model,
- the incremental change in temperature over the time step is calculated and this gives gas temperature at the end of the time step,
- pressure rise at the end of the time step is calculated,
- the reduction in mass of gas in the enclosure, resulting from the flow through the flamepath, is estimated.

To account for arcing in a methane/air atmosphere the calculation technique described above was extended to include energy released by the burning of methane. The average burning time of the methane was taken to be 50 ms, based on observation of pressure waveforms that indicated that the burning time varied between 20 and 120 ms, depending on enclosure volume. The enthalpy of the reaction was calculated for the number of moles of gas in the enclosure initially and this was divided by the burning
duration to determine the net rate of energy contributed by burning to the net energy. In estimating this contribution no account is taken of the unburnt mass of gas lost through the flamepath and this leads to overestimates of pressure rise. In calculations made for a methane/air mixture the electric field strength was assumed to be 6% greater than that of air as suggested by Murphy and Lowke(12).

4.3. Results of Calculations

The peak pressure rise measured with arcing with $x_0 = 0$ is shown in Figure 3. In all cases except in the 0.07 m$^3$ enclosure the arc was magnetically constrained and was approximately 120 mm in length. In the 0.07 m$^3$ enclosure the arc was not magnetically constrained, but the arc length is limited by the available volume, and it appears that the proximity of the wall causes additional cooling that leads to a reduction in pressure rise. In Figure 3 it can be seen that pressure rise calculated with no loss from the flamepath gives satisfactory prediction of pressure rise for enclosures with larger volumes, in which pressure rise is low and mass flow through the flamepath is also low, but predictions are greatly in excess of measurements for enclosures with smaller volumes. Also shown in Figure 3 are results of measurement of pressure rise with arcing in a mixture of 9.8% methane and air. The calculated pressure rise is also shown and gives good agreement with measurement. The temperature of the gas within the enclosure was not measured. For conditions of Figure 3, calculations indicate a gas temperature of about 1300 K for an enclosure volume of 0.4 m$^3$, and a temperature of up to 6000 K for the 0.07 m$^3$ enclosure.

The mass of gas remaining in the enclosure is shown as a function of time after commencement of arcing in Figure 4. Clearly there is a substantial loss of mass through the flamepath in the smaller enclosure, but there will be correspondingly less loss of mass in the larger enclosures under the same arcing conditions because the pressure rise causing the mass flow will be less.

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In practice the initial gap width, $x_0$, is allowed to be up a specified value that depends on flamepath length (typically 0.5 mm for a 25 mm flamepath), and therefore it is of interest to examine the effect of $x_0$ on the pressure rise during arcing. Calculations made for the 0.07 m$^3$ enclosure are shown in Figure 5.

It can be seen that increasing the initial gap width appreciably reduces pressure rise. Wider initial gap widths, however, permit the expulsion of more hot gas and molten material from the electrodes. This may increase the possibility of ignition of an external explosive gas mixture such as may occur from time to time in a coal mine.
4.4 Anomalies in Energy Estimation

It must be noted that the assumption that all the arc energy was absorbed by the air within the enclosures is not consistent with findings of other researchers, who suggest that only a fraction of the energy produced by an internal arc within an enclosure is absorbed by air. It was suggested that the rest of the arc energy was dissipated in electrode losses or transferred directly, by radiation, to the walls of the enclosure. Comparison of values of arc energy calculated from Equation (6) with the total measured energy did, indeed, show that in some cases the measured energy appeared to be about twice the value predicted by Equation (6). This could be due to the arc lengthening factor being greater than the lengthening factor, k, of 1.8 used in calculations. A value of 1.8 was chosen on the basis of a limited number of photograhic observations. However, in some experiments the arc voltage indicated arc voltage gradient of 34 V cm⁻¹ (for the assumed arc length) which was greater than the value (17 V cm⁻¹) used in all calculations. Whether this was due to the arc being longer than assumed or some other mechanism is not clear.

As was mentioned in Section 3.2 when enclosures were opened immediately after arcing, it was observed that they were full of dense brown-coloured gas that was presumably due to vaporisation of electrode material. This material would have been entrained into the arc by strong plasma jets at the arc roots. The jets would cause turbulence and rapid mixing of this material into the total mass of gas inside the enclosure. The radiation absorption characteristics of this gas could have been considerably greater than those of unpolluted air.

5. Conclusions

The pressure rise due to explosion of a stoichiometric mixture of air and methane within an enclosure is shown to be limited to 680 kPa.

A simple model has been developed for calculating pressure rise due to fault arcing in air and methane/air mixtures within flameproof enclosures. The model is based on all the energy in the arc being transferred to the air in the enclosure. It has been shown that, with a three-phase fault current of 9 kA, it is necessary to include in the model the process by which gas is exhausted from the flanges of the covers of the flameproof equipment (flamepaths). The model of the flamepath assumes that the covers are rigid, and that the flamepath width increases as internal pressure increases due to lengthening of the fastening bolts.

The model is extended to facilitate calculation of pressure rise due to arcing in stoichiometric mixtures of methane and air, by including the total energy of the exothermal reaction as an additional energy input to the air within the enclosure. A linear rate of energy release due to this mechanism is assumed, the duration of which is based on experimental observations.

The model is found to predict pressure rises that are close to experimentally-determined values.

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