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Surface temperature generation during drop weight mechanical impact and the usefulness of dynamic thermocouple measurements for predicting impact ignition of flammable gases

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ABSTRACT

The ignition of flammable atmospheres from hot surfaces arising from mechanical interactions has been a significant cause of many industrial and mining explosions. An investigation of the surface temperature generation resulting from sliding friction during short duration mechanical impacts has been carried out and the nature and usefulness of dynamic thermocouple measurement examined in the context of predicting mechanical ignition. The experimental results reveal that there is only a limited relationship between the measured maximum temperatures and the tangential energy loss during an impact. This appears to be mostly due to variation of the extent to which the tangential energy loss represents frictional loss (associated with tip sliding) rather than material deformation. Whilst an increase in impact energy tends to raise the measured surface temperature, there is significant random variation under nominally similar conditions. It is considered that this is associated with the randomness and changing nature of the contacting areas. During the small time-period of a mechanical impact, there is insufficient time for any equalisation of temperature between neighbouring contact zones to take place. With reference to the ignition of flammable gases brought about by mechanical impact, surface temperatures measured by dynamic thermocouple appear to offer only limited predictive usefulness since they could be associated with contact areas of insufficient size to transfer enough energy into the gas mixture to cause ignition. Finger-marking impact surfaces has the effect of greatly reducing the frictional energy loss but this is not fully reflected in the measured maximum surface temperature. It is concluded that ignition prediction should still be based on tests conducted with mechanical impacts taking place in an ambient flammable atmosphere.

1. Introduction

Flammable gases find use as both reagent and fuel in the chemical process industries with hydrogen being increasingly used as a fuel for buses and other vehicular transport. Hydrogen can also be generated in the storage of waste materials within the nuclear industry where the wide flammable range in air and the potential for producing large pockets enveloped in the waste sludge or arising between storage containers (Averill et al., 2018) make it a major safety hazard.

Many of the large number of incidents identified in process risk analysis are ignitions or explosions of vapours, gases or fine dusts resulting from exposure of the combustible substance to a hot surface at a temperature which exceeds the minimum or auto-ignition temperature. This has long been recognised as an important issue with hundreds of studies carried out over the past century to investigate the likelihood of ignition and explosion in mining or industrial scenarios. Much of this information can be found in the reviews by Powell (1969, 1986 and 1992), Eckhoff and Thomassen (1994), Babrauskas (2003) and Ingram (2016). Recently, a number of studies have been carried out to investigate the possibility of mechanically igniting flammable hydrogen atmospheres that arise from radiolysis or corrosion of fuel cladding material in nuclear waste silos (Jones et al. (2006) and Averill et al. (2015a,b and 2014a,b)

Whilst the processes by which a mechanical impact or interaction can lead to ignition are very well known at the qualitative level there is still much difficulty at the fundamental level. The Europe funded MECHEX project (Hawksworth et al., 2006 and Proust et al., 2007) was intended to produce a reliable method of estimating the risk of mechanical ignition but with regard to impact ignition in particular, it seems that ATEX ignition criteria is still largely based on experimental data and interpolation (Grunewald and Grätz, 2007 and Grunewald et al., 2010).

There are a number of considerations to be made in attempting to predict whether ignition of a flammable gas mixture will occur as a

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result of a hot surface generated by mechanical impact. The sufficiency of heat available from the impact surface to cause ignition will be determined by the impact temperature reached, the contact surface area of the impact and the duration of the hot surface which approximates to the contact time. In effect, the minimum ignition temperature[1] implies that the surface area of the hot surface and exposure time are sufficiently large so as not to materially influence the likelihood of ignition. Although recognizing the extent to which the minimum ignition temperature needs to be exceeded for ignition to occur in a specific situation remains a significant challenge for process engineers, any attempt to predict hot surface ignition probability must first involve knowledge of the mechanically generated temperature. It can be expected that this will primarily depend on the impact kinetic energy and the manner of its dissipation.

In a previous study (Averill et al., 2017), energy losses resulting from mechanical impacts of the kind that could occur during nuclear decommissioning of waste material were considered and measurements made of final translational and rotational velocities occurring in drop weight impacts. It was shown that energy losses determined from final impact velocities, could be accurately accounted for by those pertaining to the normal and tangential processes that occur during impact. Furthermore, the experimental results obtained clearly supported an Amontons–Coulomb friction model, suggesting that the tangential energy losses arise mostly from a process of sliding friction during impact. In both the normal and tangential processes, the elasticity of the impacting materials will result in part of the impact energy being restored as kinetic energy after impact. Any plastic deformation that occurs will absorb energy and so contribute to the energy loss. Equations were derived from a theoretical analysis to enable the direct determination of total tangential (E_{lt}) and normal (E_{ln}) energy losses from the initial impact velocity (providing the impact coefficients are already known or can be estimated).

$$E_{\ln} = \frac{0.5mv_n^2}{1+\Phi}(1-e^2) \tag{1}$$

and

$$E_{lt} = 0.5mv_n\mu k^{-2}(1+e)[\mu v_n(e+1)(d_d^2 e_m - k^2) + 2v_t(k^2 - e_m d_c^2) + d_c d_d e_m(2\mu v_t - (1+e)v_n)][1+\Phi]^{-2} \tag{2}$$

Where

$$\Phi = e_m d_c(\mu d_d - d_c)/k^2 \tag{3}$$

An important new finding of the study was that contamination of the impacting surfaces by finger marking resulted in substantial change to the impact coefficients with considerable reduction of the impulse ratio or friction coefficient and change in the nature of the impact.

To obtain a realistic appreciation of the likelihood of an ignition event occurring when mechanical impacts occur in the presence of flammable atmospheres, it is necessary to consider how this frictional energy dissipation relates to surface temperature increase and the onset of flammable gas mixture combustion. Together with the exposure time and extent of the exposed surface area, the temperature of the hot metal impact zone is a major factor in determining whether ignition occurs or not. A large temperature gradient in the surrounding flammable gas mixture will develop normal to the hot surface that may be sufficient to raise the temperature beyond the auto-ignition temperature for the gas mixture (Averill et al., 2015a; Kumar, 1989). As Kumar points out, if the surface is maintained at the auto-ignition temperature, ignition can only occur if the gas mixture is contained for sufficient time within an adiabatic enclosure so that the gas temperature eventually reaches that of the surface. During a short duration impact event, however, major heat losses will occur from the kernel of gas mixture in contact with the surface so that the temperature of the hot impacted surfaces must be considerably greater than the auto-ignition temperature (i.e. bounded by the adiabatic flame temperature) for ignition to occur. To characterise an impact event, in terms of its likelihood to cause gas ignition, it is necessary to determine the maximum surface temperature the contact duration and surface area of the impact zone.

There are difficulties in making temperature measurements of contacting surfaces subject to sliding friction and understanding their meaning. This is especially true where they are of a transient nature during mechanical impacts that last in many cases for less than a millisecond. Whilst high-speed pyrometers have become available in recent years with response times of a few microseconds, there is still the difficulty in determining temperature at the precise time of impact rather than after contact has ceased. An innovative radiometric technique has also been recently developed to determine local temperatures at sliding interfaces with fast sampling (Rowe et al., 2013) but its application would involve considerable difficulty in imaging a short duration impact event. One approach, capable of measuring rapidly changing temperatures arising during sliding contact or impact, is to use a dynamic thermocouple arrangement: a thermocouple junction with dissimilar metals is created at the interface between the contacting bodies with rapid response recording of the thermoelectric emf. Averill et al. (2013, 2014c) have studied the generation of interfacial temperatures with sliding metal surfaces. Experiments were carried out using dynamic thermocouples to determine surface temperatures arising over a wide range of loading and sliding velocity conditions: an appreciable degree of similarity was found with calculated values using equations derived from thermal analysis. Determination and prediction of surface temperatures resulting from an impact is more difficult than is the case with simple sliding contact due to the short duration and complexity of the impact mechanics. In particular, there is no full understanding of the nature and meaning of dynamic thermocouple measurement made during a mechanical impact.

This paper reports an experimental programme to investigate the relationship between the frictional energy losses occurring during drop weight mechanical impact and measured surface temperatures using a dynamic thermocouple. Of special interest is the usefulness of such measurements in predicting the likelihood of flammable gas ignition by mechanical impact. To facilitate further discussion, the theoretical relationship between the instantaneous contact thermoelectric emf and that recorded during measurement is first considered.

2. Thermoelectric effects: relationship between measured dynamic thermocouple measurements and the impact interface temperature

There are several electrical effects possible when opposing metal surfaces slide against each other during impact. Although charge transfer can occur due to tribo-electrification (Chiou et al., 2003) this is unlikely to represent a significant contribution to the generation of emf with metals of high electrical conductivity. Consequently, the measured emf is assumed the same as with non-moving contacts.

Charge carriers diffusing from the junction of two dissimilar metals in sliding contact towards a cold junction establish a direct relationship between the temperature gradient at the interface and the generated thermo-electrical emf. In a dynamic thermocouple with the junctions between contacting metals A and B being held at two different temperatures, a Seebeck emf is generated in accordance with

$$\varepsilon_{AB}(T_1, T_2) = \int_{T_2}^{T_1} [S_A(T) - S_B(T)]dT \tag{4}$$

This is equivalent to the sum of the Peltier and Thomson emfs in the circuit

$$\varepsilon_{AB}(T_1, T_2) = \Pi_{AB}^{T_1} - \Pi_{AB}^{T_2} + \int_{T_1}^{T_2} (\sigma_A - \sigma_B)dT \tag{5}$$

where $\Pi_{AB}^{T_1} - \Pi_{AB}^{T_2}$ is the Peltier emf generated at the dissimilar metal

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[1] As determined in standard tests. E.g. BS EN 14522:2005.