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Ignition of a hydrogen–air mixture by low voltage electrical contact arcs

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ABSTRACT

This article presents an experimental and computational study of ignition caused by a low voltage electrical contact arc. The contact arc is a transient electrical discharge which occurs due to movement of electrical contacts, for example, when two energised electrodes are separated. The physical properties of this discharge are significantly different from the more conventional high voltage spark. Its potential to cause ignition is an important consideration in international explosion protection standards. As these standards are based on unreliable empirical methods, a more fundamental investigation is warranted. This study uses a specially designed apparatus and electrical circuit to create the contact arc in a hydrogen–air mixture. The transient development of the resulting flame kernel is observed using Mach–Zehnder interferometry with high spatial and temporal resolution. These experimental results are compared to simulations of a 3-D reactive flow model with detailed chemical kinetics and molecular transport. A quantitative comparison is effected by the generation of synthetic optical phase plots from the simulation output. This comparison showed reasonable correspondence between the simulated and measured flame shape. Ignition delays and thresholds were, however, under-predicted by the model. The comparison was complicated by significant statistical scattering in the experimental results. Additional investigations into the sensitivity of the model showed good robustness to grid size variations, and that inclusion of a simplified consideration of heat transfer through the electrodes produces small differences in flame shape and ignition delay.

1. Introduction

The use of low powered electrical equipment in the presence of flammable gas can present a risk of explosion. A potential source of ignition resulting from such equipment is the electrical contact arc. Ignitions resulting from this type of electrical discharge have been the subject of several historical studies, culminating in the development of an internationally standardised concept for managing contact arc ignition risk [1]. These investigations were mostly empirical in nature and were limited to observing the incidence or non-incidence of ignitions for contact arcs resulting from various types of electrical circuits. The aim of this study is to enable a more a fundamental understanding of this process through the use of diagnostic and computational techniques.

1.1. Intrinsic safety

Intrinsic safety is the name given to the standardised explosion protection concept, which, among other goals, aims to manage the risk of ignitions posed by contact arcs in electrical equipment. This is accomplished by sufficiently limiting power output of an electrical circuit, so that, even if contact arc discharges occur, they are incapable of igniting a flammable gas mixture. The power limitation is verified by an empirical test device known as the Spark Test Apparatus (Fig. 1). This device consists of a tungsten wire anode and cadmium disc cathode rotating against one another, both of which are enclosed in a test cell containing a flammable gas mixture [1]. Contact arcs are created when electrical power output from a device under test is applied to these electrodes, and the absence of ignition within a defined number of revolutions is considered to indicate an acceptably low ignition risk. This testing method has been found to suffer from extremely poor reproducibility of results, likely due to the uncontrolled way in which contact arcs occur [2]. It is anticipated that the fundamental understanding gained from

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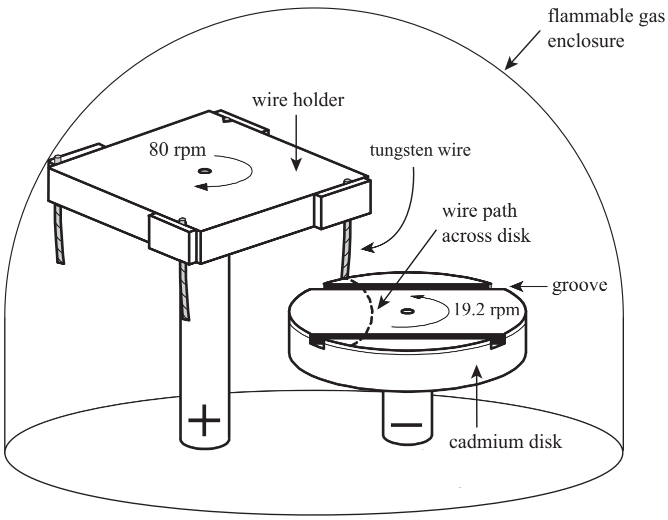

Fig. 1. The standardised Spark Test Apparatus (STA). A circuit is connected to the marked positive and negative terminals to test for contact arc ignition hazards.

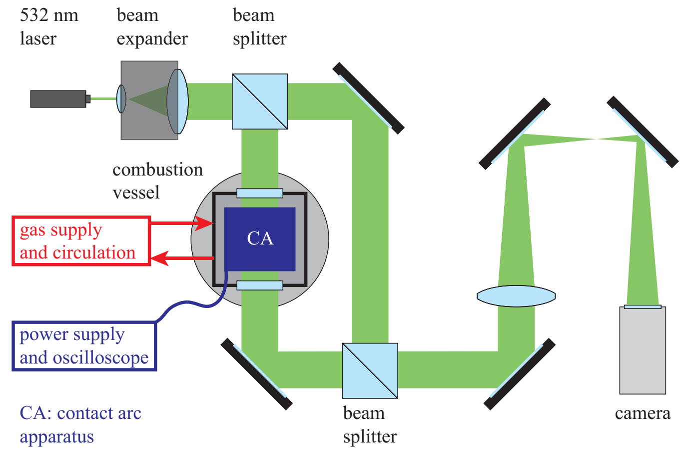

Fig. 2. Schematic depiction of the experimental setup.

this work will lay the groundwork for developing more reliable methods of safety assessment.

1.2. The contact arc

"Contact arc" is one of several terms used to describe electrical discharges which can result when contact is either broken or made between two electrodes. This study considers those which occur when contact is broken, also known as "break sparks". Unlike conventional spark discharges, contact arcs can occur at voltages significantly below the 300 V minimum required for dielectric breakdown of air as predicted by Paschen's law [3]. They also do not strictly conform to conventional definitions of an arc discharge, being shorter in duration and occurring at significantly lower currents. Typical values for a contact arc are voltages from 15–40 V, currents from 50–300 mA and a duration of 30–200 µs.

The electrode material has a significant influence on the formation of contact arcs. The initiation process, though not well understood, is thought to rely on a combination of evaporated metal and field emitted electrons from the cathode material. A recent experimental study additionally found the discharge plasma to be mainly comprised of cadmium vapour [4]. Additionally, the minimum voltage at which the arc can form, a combination of anode and cathode "fall voltages", is a property of the electrode material. The cadmium–tungsten electrode combination was chosen by the earlier studies and the standard for this reason, as it possesses fall voltages lower than other contact materials [5]. Cadmium additionally has a low boiling point and conductive oxide, both of which may aid the initiation of contact arcs.

2. Experimental investigation

A description of the experimental setup is provided in Fig. 2. The combustion vessel and combustible gas mixture details are provided in Section 2.1. Details of the contact arc apparatus and associated electrical equipment used to ignite the gas, as well as the measurements used to characterise the contact arcs are given in Section 2.2. The resulting ignition was observed using interferometry, which afforded a spatial and temporal characterisation of the gas field near the ignition source. The interferometer and associated post processing of image data is described in Section 2.3.

2.1. Combustion vessel

Ignition experiments were performed in a 2.48 L vessel with internal dimensions 0.114 m × 0.114 m × 0.191 m. The vessel was evacuated to below 10 Pa and filled with hydrogen, oxygen and nitrogen using the method of partial pressures with a 10 Pa accuracy. The gases were mixed by a circulation pump and left to settle in order to reach quiescent conditions. Initial conditions were 101.3 kPa, 298 K, the hydrogen mole fraction was 0.21 and the ratio of oxygen to nitrogen was 1:3.76, simulating air. The vessel was equipped with lateral viewing windows providing optical access for interferometric measurements.

2.2. Contact arc apparatus and electrical measurements

A special apparatus was designed to create the contact arc discharges. This device, depicted in Fig. 3 was modelled on the standardised apparatus of Fig. 1, but modified to generate arcs in a more controllable manner. Specifically, tungsten and cadmium as the anode and cathode materials respectively were retained, as was the sliding action of the wire anode over the cathode. The counter-rotating motion of the contacts was, however, replaced with a linearly actuated wire and stationary block. Additionally, the stationary cathode block was equipped with a 4 degree-of-freedom positioner to allow precise adjustments.

The electrodes of the contact arc apparatus were energised with an adjustable constant current power supply. As noted in [6], this allows a greater degree of control over the amount of energy dissipated by the contact arc. Voltage and current waveforms of the contact arcs were recorded using a digital storage oscilloscope (LeCroy Wavesurfer 44XS-a), allowing the instantaneous power and total energy dissipated in the arcs to be calculated. An example of current and voltage waveforms for a contact arc can be seen in Fig. 4. Here the start of the arc is signified by a sudden rise in voltage from 0 to v_{fall} (the fall voltage as described in Section 1.2). The arc ends when current falls from i_{arc} to 0 and voltage reaches v_{end}. The observed value of $v_{fall} \approx$ 10 V corresponds closely to the fall voltage for a cadmium cathode in air reported by [5].

The fall voltage is an important consideration for the measurement of power and energy dissipated in the arc. Although it is a significant proportion of the total voltage drop, it is concentrated within or near the electrode – the so called "fall region". Historical studies have found that power dissipated in this region, equivalent to the fall voltage multiplied by circuit current, does not appreciably contribute to ignitions [7]. A more accurate calculation of the energy dissipated in the gas is thus obtained by multiplying