Fire Safety Journal 89 (2017) 7–15

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Review

Electric arc explosions—A review

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ARTICLE INFO

Keywords:
Arc pressure
Electric arcs
Electric switchgear
Electrical accidents
Explosions
Shock waves

ABSTRACT

When an electric arc is created, a pressure event occurs. There can be two aspects to this: the shock and sound waves propagated from the expanding arc channel, and the bulk pressurization of the enclosure, if arcing is taking place within a closed volume. The present paper is the first systematic review of the research on both these pressure phenomena. Quantitative studies on electrical arc explosion pressures date back to the 1920s, although arc pressures generated by lightning, which is a type of electric arc discharge, have been studied since the 1700s, but understanding of the phenomena is still not complete or exhaustive. Experimental data are compared to theoretical predictions. It is shown that in an enclosed volume some extremely high pressures can be generated, if the arc current is sufficient. Such pressures can destroy buildings and mechanical equipment and cause injuries or death to nearby individuals. Even without enclosures, the shock waves produced from high energy arcs can cause injuries, although arc flash injury may be of greater concern. Injury potential generally requires that high currents be available, and serious damages or injuries are not associated with low-energy arcing occurrences.

1. Introduction

An electric arc is defined as a continuous, luminous discharge of electric current having a thermalized plasma and supported by thermionic emission from the cathode [1]. A plasma is a partially-ionized, electrically neutral gas, while 'thermalized' means that it is a hot plasma. Physically, an arc spans between two electrodes (metallic objects) maintained at a sufficient voltage difference. Geometrically, there is no standard shape for an arc. The shape of an arc is determined by the apparatus where it is created, and furthermore an arc typically changes its shape with time. The science of electric arcs is discussed in detail in numerous textbooks, e.g., Meek and Craggs [2].

Electric arcing in circuits with sizable maximum short-circuit current capacity can be a highly energetic effect. In fact, buildings have collapsed due to arc pressure, since in an enclosed space some surprisingly large pressures can be built up. 'Arc flash' is the thermal radiation component associated with energetic electric arcs, and it has received a great deal of study in recent years since thermal radiation has been a cause of serious burn injuries to electricians [3]. Consequently, computational methods and research have focused on the design of appropriate protective clothing. For arc pressures, however, no comparable activity has taken place. In fact, the literature is sparse and not systematic on this topic. It is the purpose of this paper to provide the first-ever review of electric arc explosions. The emphasis is placed on pressures developed and on the calculational methods available for these, along with experimental data that have been published. Some of the results are strikingly high. For instance, in one test explosion overpressures of 83 atm were obtained. The magnitude of this can best be appreciated by considering that a fuel-air deflagration will typically attain only around 7 – 8 atm, barring pressure-piling effects or other turbulence enhancements. During normal operation of a circuit breaker, arc pressures of roughly 3 atm magnitude can be expected [4], but these devices are designed to sustain the pressures generated by the normal arcing associated with circuit opening.

With regards to the energy supplying the arc, arcs can be of three types: (1) discharge of a fixed amount of stored energy (e.g., a capacitor; a current transformer); (2) DC power sources; or (3) AC power sources. Lightning strikes are the most important form of stored energy discharge, since capacitive discharge tends to be confined to specialized situations and is uncommon as a source of industrial accidents. Since most of the power transmission and distribution networks are AC, the bulk of the research available has focused on AC arcs. But heavy-power DC systems also exist and are important in certain industries (e.g., electric train propulsion). DC arc explosions are fundamentally different since there is no 'zero-crossing' in DC. In AC circuits, an arc will extinguish at 2× the power frequency (e.g., at 100 or 120 Hz), although it may reignite very shortly afterwards. In DC circuits, this extinguishing characteristic does not exist, and arcs will generally extinguish only due to external circuit interruption or due to

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http://dx.doi.org/10.1016/j.firesaf.2017.02.006
Received 8 August 2016; Received in revised form 15 February 2017; Accepted 16 February 2017

excessive electrode consumption. Most aspects of arc behavior only depend on arc current and arc power, and not on the type of power supply, but where the type of power supply does matter, this will be considered. The discharge of a fixed amount of energy is termed a *spark*, while a sustained discharge is an *arc*, but again this distinction will generally be seen not to affect the analysis of results.

Arc explosions are not rare in industry, and in other situations where 480 V, or higher, voltages are utilized, but published case histories are scarce. Neither of the two large electrical accident compilations [5,6] mentions the subject. Lee [7] published four brief case histories, Crawford et al. [8] documented seven case histories of arc explosions inside motor terminal boxes, include one fatality, while Heberlein et al. [9] described two non-fatal explosions inside motor control centers. The best-known incident was in an Atlanta high-rise building that took place on 30 June 1989. The fumbling of an electrician replacing a fuse caused a 480 VAC bus duct explosion [10] and the explosion and subsequent fire led to five fatalities.

Lightning strikes can lead to arc explosions in any type of premises. In 1773, Lind demonstrated that if a conductor from a lightning arrester is run down through a house, but with a small gap in this conductor, this can form a spark gap and a strike to the arrester can result in an arc explosion capable of destroying the house [11]. Individuals have been bodily knocked over when in proximity both to electrical fault arcs and lightning strikes, although interestingly often there have been negligible injuries to the individual knocked over [12]. But in cases where roofs collapse, the outcome may be traumatic if persons are present underneath.

Eardrum rupture can be expected at explosion overpressures of 19 kPa (10% probability) or 45 kPa (50% probability), while death due to lung damage is 120 kPa (10% probability) or 141 kPa (50% probability). The above values come from an extensive statistical study by Eisenberg et al. [13]; older data are somewhat different, but not greatly. In any case, they indicate that it does not take massive overpressures for injury or death to result from explosion pressures.

Only arc explosions in gases will be reviewed here, even though arc explosions in electrical insulating liquids can be of importance and arc explosions underwater are of some specialized interest. Apart from true arc explosions, conventional fuel-air explosions can also arise due to electrical causes. Perhaps the most common type of explosion associated with electricity is where an electric spark ignites a flammable gas mixture or dust cloud. These explosions can be severe and destructive, but are not covered here, because the electric power does not provide the energy for the explosion, instead, it is the chemical oxidation reaction which serves as the energy source. Also excluded are explosions in manholes, underground ducts, and similar installations which may entail both fuel-air explosion and arc explosion aspects. Transformer explosions [14] also involve some arc explosions aspects, but they are typically complicated and will likewise not be covered here.

An arc explosion arises due a very rapid heating of air or other medium. In the process, electrical energy is converted into other forms of energy: dissociation (breaking up of molecules, e.g., separating O_2 into 2O), ionization, and heating of the gas, including its compression; thermal radiation; and conduction losses into adjacent solids such as electrodes. In addition, some electrode metal is vaporized and this contributes to the total volume which is being explosively heated, yet, the role of chemical reactions has only recently been explored. Thunder is an acoustic manifestation of an electric arc explosion and has been studied for centuries (the currents involved in a lightning discharge are typically 20 – 200 kA, which is in the same range as for serious industrial electric arc accidents). Yet only in the last decade has there been some understanding achieved of the relative importance of the mechanisms involved, primarily due to Graneau and coworkers [15]. They demonstrated that thunder could not be adequately explained solely by thermal or electrodynamic effects, and this conclusion would pertain to arc explosions in general. In one experiment, they used an 8 μs duration capacitive discharge and showed that the energy measured from the arc was 124% of the energy stored in the capacitor. The 24% gain was not a measurement error, but represented chemical energy liberated by breaking chemical bonds. Specific pathways were found to include dissociating N_2 and O_2 molecules into atoms, then forming products such as O_3 and NO_X. Researchers have generally ignored the need to account for stored chemical energy, thus published heat balance calculations are likely to be subject to error, especially for short-duration arcs. Graneau et al. also noted that in the lightning community, high-current, short-duration discharges are termed ‘cold lightning.’ This is not hyperbole and they found that while discharges mechanically tore a piece of paper inserted into the path of the arc, they did not ignite the paper nor even char it. The paper could be ignited, however, if placed in contact with the electrodes. They also observed that lightning hitting water did not generate steam.

2. Shock waves generated from electric arcs

If in a gaseous medium there is an abrupt change in pressure, temperature, or volume created at some location, a wave will be generated which will propagate through the medium. The wave can be a sound wave, a shock wave, or both, depending on the characteristics of the source. In the case of an electric arc, while a shock wave will be generated and it is audibly perceived as an explosion (unless of very small scale), the shock wave does not constitute a detonation, which would require that the shock wave be supported by an exothermic reaction occurring behind the shock front.

For subsonic sound waves in air, the decay in pressure with distance from the source goes as $1/\sqrt{r}$ for the infinite-cylinder geometry and $1/r$ for the sphere. But for shock waves, these simple wave-equation relationships are not applicable. A reasonably short arc will be represented by a short cylinder, but this is not a geometry that lends itself to simple theoretical solutions. Baker presented calculated data on a point sources [16], along with experimental data on bursting explosions of short cylindrical vessels [17] and spherical vessels[17]. The curvature in these relationships (Fig. 1) show that, unless only examined over small intervals, the actual relationship is not of a power-law type. In this figure, the non-dimensional scaling variables used are $\overline{P} = \Delta p/p_o$ and $\overline{R} = r/\sqrt[3]{E/p_o}$, where Δp= pressure rise (Pa), p_o = ambient pressure (Pa), r = radius (m), and E = energy (J). But, in addition, it should be noted that the actual shape of the curve will depend on the rate at which the energy is delivered, and this can have a range of variations.

Turning now specifically to the electric arc, when breakdown is initiated, a narrow conducting filament first bridges the gap, and then it grows rapidly in diameter until it reaches an ultimate value and the ‘arc

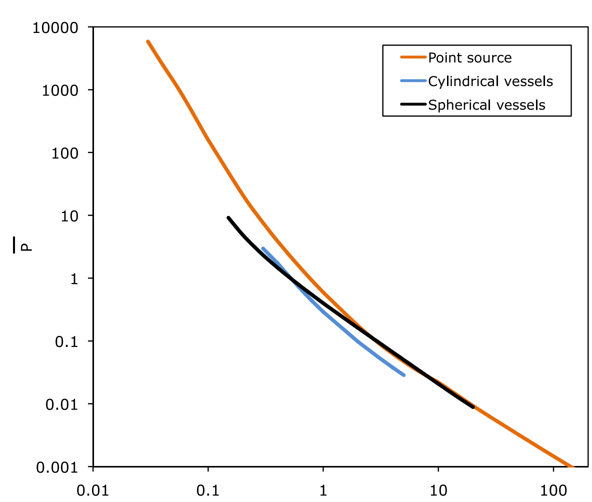

Fig. 1. Shock wave overpressure scaling for several geometries.