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Research paper

Lumped Parameter Analysis of Bridge Wire in an Electro Explosive Device of a Power Cartridge for Water-Jet Application: A Case Study

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Abstract: In an armament system an electro-explosive device (EED) essentially converts electrical energy into heat which further initiates the explosive train with its accompanying temperature rise. The first function of an EED in a power cartridge is to provide adequate electrical current to cause ignition of the highly sensitive explosive i.e. lead styphnate. The electrical current accomplishes ignition by heating the bulb of lead styphnate which produces enough heat to cause the booster to ignite. The booster which is in the immediate vicinity augments the ignition of the propellant further. The igniter must be held firmly in place with the booster in the tube. Understanding of the initiation of explosives using a bridge wire in EEDs is important for engineers, designers and scientists to develop new theories. In this research article, theoretical and experimental work has been reported pertaining to bridge wire devices in power cartridges for water-jet applications. The objective of the present research work is to use lumped parameter analysis of a bridge wire in an electro explosive device of a power cartridge for water-jet application. A lumped parameter theory is proposed for the analysis of

EEDs. A time constant of 3.35 s has been determined using the lumped parameters. The Biot number is less than 0.1 indicating that transient phenomenon is applied.

Keywords: all fire current, bridge wire, electro explosive devices, igniter, lumped parameter, no fire current, power cartridge, water-jet disruptor

1 Introduction

1.1 Applications of EEDs

Electro Explosive Devices (EEDs) are one shot explosive or pyrotechnic devices that are widely used in gas generators, aerospace, weapons, armaments, civil blasting equipment and other fields for military systems as the initiating element in an explosive train. EEDs perform a variety of roles, such as initiating components in explosive trains, gas generators and sources of heat or mechanical energy to perform other munition system functions. A pyrotechnic gas generator is a pyrotechnic composition, known as the "gas generator" [1, 2]. It consists of a high resistance wire (bridge wire) surrounded by a heat sensitive pyrotechnic composition to form a bulb [3]. A coating of a material such as nitrocellulose lacquer is normally applied over the bulb to protect and strengthen the composition. It gives a quick response time, high reliability, and a safe and steady performance. It is activated by the application of electrical energy using a DC power supply and a capacitor. EEDs are used to ignite a variety of energetic materials including explosives, propellants and pyrotechnics to generate hot particles, flame and gas pressure. EEDs transform electrical energy into thermal and explosive energy in order to produce detonation output. They convert electric energy into heat, and transfer this heat to the primary explosive. As the temperature reaches the explosive ignition point, the initiators detonate [4]. Thermal explosion of energetic materials due to bridge wire heating is a complex phenomenon involving a series of physiochemical processes which depend on the sample geometry, the heating rate, the chemical and physical properties of the material and the strength of the axial and radial confinement. The delay in a bridge wire device is of millisecond duration. No fire and all fire current levels mainly depend on the physical construction and energetic material of the explosive device.

Hot bridge wire explosive devices require few a millijoules of energy for initiation. However, they are unsafe. Exploding bridge wire based explosive devices are safe but are unsuitable for use in electronic fuses due to the high voltage required for their operation [5]. EEDs consist of a pyrotechnic igniter containing the resistance wire, squib holder, and booster composition followed by the propellant. They use electrical energy as the initial stimulus to initiate the igniter composition at the start of the explosive train. When an electric current is passed through it, the resistance wire ignites the composition by the Joule effect. The general layout for an explosive train of power cartridges where EEDs are used is shown in Figure 1.

Figure 1. The general layout for an explosive train of power cartridges

EEDs are extensively used in aerospace vehicles as volume and weight are important in these applications. They deliver many times the output energy of other possible movers such as springs or compressed gas cylinders [6]. Energy is released in a few milliseconds and hence extremely fast acting. Furthermore, they have a long storage life for which no maintenance is required. They function successfully in all environmental conditions which has proved reliable in actual use. They play very crucial roles in performing various tasks. Their important applications are:

– as a means of initiation in armament system like guns, rockets, missiles, warheads and the Space Shuttle,
– pyro cartridges as the gas generator to operate various escape aid systems in fighters as well as trainer aircraft,
– used to provide delay between two successive events to achieve desired objectives,
– widely used in ground applications for initiation of explosive trains for demolition or burning of unserviceable ammunition and disruption of suspect objects such as water-jet applications to disrupt IEDs and de-armour disruptor systems [7, 8],
– to suitably initiate an impulse cartridge so as to get the desired maximum pressure,
– release of externally carried stores (*i.e.* bombs or weapons from military aircraft) so as to achieve positive separation from the parent aircraft and store,
– for cutting of cords, emergency brake application and to operate fire extinguisher bottles.

1.2 Background information

An investigation of the ignition of TATB and HMX samples by means of local heating using a wire was performed at different rates of heating [9].

Various experimental, theoretical, and simulation studies have been reported in the past few decades with the aim of improving the understanding of the physics of the thermal ignition of explosives. An energetic material used in EEDs in confinement may absorb heat energy from its surroundings leading to it undergoing rapid chemical decomposition and explosion. A phase-changing polymer bonded explosive material in a cylindrical confinement was subjected to rapid heating corresponding to fast cook off and was studied by the thermal ignition process. The authors developed a computational model for solving two dimensional unsteady heat transfers due to multi-step chemical reaction caused by heat generation and phase changes [10]. Electrical energy applied by a bridge wire dissipates, part of the input energy going into heat loss from the wire and part going into heating the wire. When there is a temperature rise in the wire the power transfer will be affected so that some form of nonlinear equation in needed to describe it [11]. EEDs' initiators utilise micro wires as they have a large surface area and high electrical and thermal conductivities. This helps to enhance the pressure output and reduces the voltage input required for ignition. Jang *et al.* [12] investigated the electro-thermal behaviour of small diameter copper and gold micro wires which ignited quickly. An analysis of the initiation process of EEDs was carried out by considering the steady state flow of water through a barrel having a small hole in its base. The hole at the base of the barrel was modelled as a linear hydraulic resistance [13].

The onset temperatures in hot wire ignition of AN-based emulsions have been reported [14]. Before the ignition of ammonium nitrate (AN)-based emulsions it is possible to detect the onset temperatures using a consistent methodology. The experimental results have been shown to be in good agreement with the predictions of a theory that was developed based on the energy balance of the endothermic effects of water vapourization and AN dissociation. It is not related to the ignition but rather to the phase change of the water-based AN emulsions [15].

1.3 Assumptions in lumped parameter analysis

The following assumptions are made about the thermal ignition process of lead styphnate:

- Negligible heat convection due to absence of bulk fluid motion.
- Heat conduction is present in energetic materials for both solid and liquid phases.
- The confinement wall is treated as adiabatic except the heating surface.

2 Hot Wire Initiation Theory

2.1 Assumptions

When applying electrical energy to the bridge wire/explosive, the energy is dissipated into the explosive and header. An explosive reaction process occurs in an EED as the temperature of a small amount of the explosive is raised above its ignition temperature due to the heat input by the application of electrical energy. Alternatively the explosion of a bridge wire that takes place due to the application of an electrical pulse may cause detonation either directly or indirectly such as when the explosive is struck by a flyer launched due to the explosion. The reaction process will depend upon on the state of the explosive, its type, the rate of energy input and the degree of confinement.

The energy required to fire a hot wire initiator is roughly proportional to the volume of the bridge wire. The threshold temperature increases as wire diameter is reduced. The energy required per unit volume increases with decreasing wire length. A lumped equivalent circuit has been used to describe the conversion mechanism [16, 17].

The basic differential equation as a lumped thermal model related to the rise in bridge wire temperature is given below.

$$C\frac{dT}{dt} + \gamma T = P = I^2 R_0 (1 + T\alpha) \tag{1}$$

where C is the specific heat (W·s/°C) of the bridge wire and **γ** represents the rate of heat loss factor (W/°C), T is the temperature increase (°C), t is the time (s), P is the power (W), R_o is the initial resistance (Ω), α is the temperature coefficient of the resistivity of the bridge wire and I is the current (A).

Alternatively power is also expressed as:

$$P = (\text{Energy / time required}) = V\,(Q/t) = VI \tag{2}$$

where $Q/t = I$ and Q is a charge in Coulomb.

As per Ohms law $V = IR$, substituting in Equation 2, gives:

$$P = I^2R \tag{3}$$

The heat produced (H) in the bridge wire in time t is expressed as:

$$H = I^2Rt \tag{4}$$

As the current changes, the heat produced also changes.

At a steady state condition, with minimum power at a constant bridge temperature, the power equals the heat transfer ($q = H/t$):

$$P = I^2R = q \tag{5}$$

2.2 Bridge wire pyrotechnic system

The bridge wire of an EED is a fine resistance wire. It converts electrical energy into heat. The wire is in contact with a highly sensitive explosive mixture. As the pyrotechnic ignition process occurs next to the bridge wire, one has to look at only that portion of the total squib that is in contact with the bridge wire. It can receive heat from the bridge wire. Heat is generated within the bridge wire when the firing current passes through it for a very short period of time. Some of this heat is conducted into the lead wires, some into the nylon header, but most of the heat leaving the bridge wire is conducted to the pyrotechnic composition *i.e.* lead styphnate. Only a small portion of the total heat generated within the bridge wire is conducted away, and most of the generated heat goes into heating up the bridge wire. Neglecting axial conduction of heat to the pins that are within the bridge wire, the bridge wire should be at the same temperature along its length. The energy balance equation states that the energy supplied to the ignition system is always equal to the heat gained plus heat lost to the surroundings. The critical factors affecting bridge wire ignition depends on its geometry (shape and size), the physical properties of the wire, its temperature and the quantity and type of explosive [18].

2.3 Mathematical forms of lumped parameter analysis

Solutions to the transit heat flow problems are obtained using the lumped parameter analysis. This analysis presumes that the solid has an infinitely large thermal conductivity. The internal conduction resistance is then so small that heat flows to or from the solid are controlled primarily by the connective resistance. Within the solid, temperature gradients are negligible. Generally the temperature of the body T is given by a function of x, y, z and t [19], *i.e.* $T = f(x, y, z, t)$.

The general solution of the temperature is not easily obtained. Temperature, though changing with the time, is nevertheless uniform throughout the solid at any time.

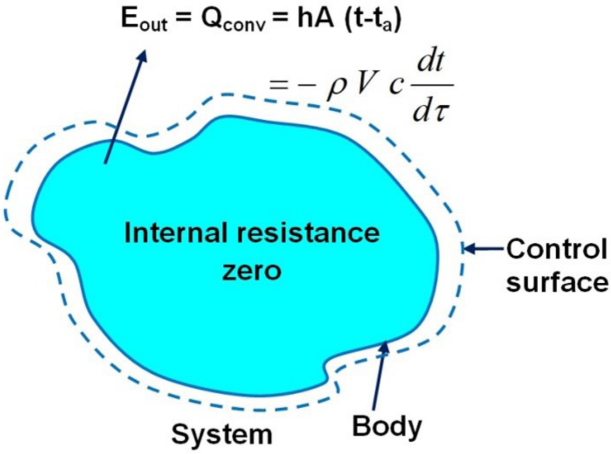


Figure 2. Lump material for unsteady heat conduction

Consider a simple case of heating a bridge wire whose internal resistance is zero. As the internal resistance is zero and heat transfer is in an unsteady state, the body's temperature changes at all times and there is no heat flow inside the body due to conduction. Figure 2 shows a lump of material comprising the system of interest. Consider a body having surface area (A), volume (V), material density (ρ), thermal conductivity (k), specific heat (C) and initial temperature (t_i) exposed to an ambient temperature (t_a). The transient response of the solid can be determined by relating its rate of change of internal energy with heat exchange at its surface.

The heat lost by the body by convection equals the change of internal energy with respect to time:

$$-\rho V C \frac{dT}{dt} = h A(t - t_a) \tag{7}$$

$$\frac{dT}{dt} + \frac{h A}{\rho V C}(t - t_a) = 0 \tag{8}$$

It is multiplied by a negative sign to make the heat positive because dT/dt is negative. The term ρVC is called the lumped thermal capacitance. The term ($1/hA$) is the resistance to convection heat transfer, where h is the convection coefficient for the flow of air on the bridge wire surface.

This expression can be rearranged and integrated; temperature T of the body at any time t substituting $m = \rho \cdot V$, *i.e.* mass of the body:

$$\int \frac{dT}{(t - t_a)} = -\frac{h\,A}{m\,C} \int dt \tag{9}$$

$$\log_e (t - t_a) = -\frac{h\,A}{m\,C} t + C_1 \tag{10}$$

The integration constant C_1 is evaluated from the boundary conditions: at $t = 0$, $t = t_i$ (initial surface temperature) of the body temperature at the start of the cooling or heating process. Therefore $C_1 = \log_e(t_i - t_a)$ and hence:

$$\log_e (t - t_a) = -\frac{h\,A}{m\,C} t + \log_e (t_i - t_a) \tag{11}$$

or

$$\log_e \frac{(t - t_a)}{(t_i - t_a)} = -\left(\frac{h\,A}{m\,C} t \right) \tag{12}$$

$$\frac{(t - t_a)}{(t_i - t_a)} = \exp\left(-\frac{h\,A}{m\,C} t \right) \tag{13}$$

Putting $(t - t_a) = \theta$ and $(t_i - t_a) = \theta_i$ in Equation 13:

$$\frac{\theta}{\theta_i} = \exp\left(-t \frac{h\,A}{m\,C} \right) \quad \text{or} \quad \frac{\theta}{\theta_i} = \exp\left(-t \Big/ \frac{m\,C}{h\,A} \right) \tag{14}$$

This above equation helps to determine the temperature at a given time or the time required to reach the temperature. Equation 14 gives temperature distribution in the squib wire for Newtonian heating and indicates that the temperature rises exponentially with time. The process where the internal resistance is assumed negligible in comparison with the surface resistance is called Newtonian cooling or heating.

The lumped model system analysis can be thought of as an electrical analogy in terms of a resistance-capacitance RC circuit and the process of heating/cooling as charging/discharging the capacitor. Here ρVC is the thermal capacitance and $1/hA$ is the resistance to convective heat transfer. The equivalent thermal circuit for lump capacitance is illustrated in Figure 3. When the switch is closed, the squib is charged to a high temperature potential. On opening the switch, the thermal energy is dissipated through thermal resistance and the temperature decays with time.

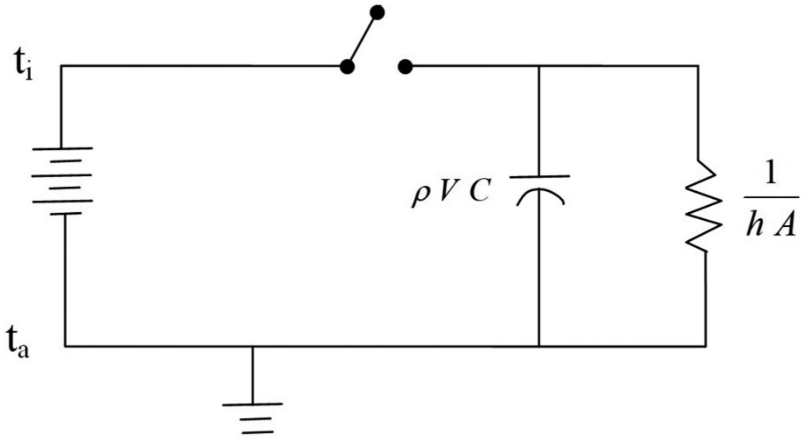
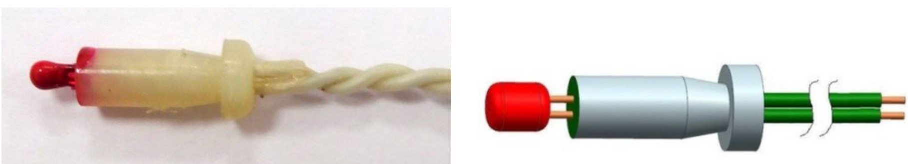


Figure 3. The equivalent thermal circuit for lump capacity method

3 Experimental

3.1 Materials and methods

Figures 4(a) and 4(b) depicts the solid model and schematic image of the squib used in conducting the water-jet disruptor experiment to initiate the cartridge. It is made of a highly sensitive material such as lead styphnate pasted on a nichrome bridge wire, the moulded plug is made of nylon material and Ni-chrome wires are used to make electrical connection.



(a) (b)

Figure 4. The solid model of the squib (a) schematic image of the squib (b)

The physical properties of EED-polyamide and nichrome wire materials used in this construction are given at Table 1.

Table 1. Specification of EED-Polyamide and Ni-chrome wire

EED-Polyamide

Density	0.941-0.965 g/cm^3
Tensile strength	74 MPa (Min)
Melting point	255-268 °C
Squib composition	Lead styphnate

Ni-chrome wire

Wire diameter	48 SWG [@ Ø 0.040 mm]
Resistivity	1.44 µΩ-m
Resistance of wire	980 ± 10% Ω/m
Temperature coefficient resistivity	100 ppm/*°C*
Resistance	867 Ω/m

Physical property

Melting point	1400 °C
Density	8.2 (g/cm^3)
Specific heat	450 (J/kg/°C)
Heat capacity	0.502 J/g·°C
Tensile strength	1200 (N/mm^2)
Thermal conductivity	11.3 (Wm^{-1}/°C)
Modulus of elasticity	2.2 ×10^{11} Pa
Thermal expansion	13 ×10^{-6} /K

3.2 Manufacture of squib for power cartridge

The EED is the heart of the power cartridge used in a water-jet disruptor. It consists of a bridge wire made of nichrome, an igniter mixture pasted on the bridge wire and a nylon body. This is manufactured using a die and punches in a hot moulding process. After this, the bridge is soldered onto two conductors. The igniter paste is then applied to the bridge wire of the EED. It is then dried at 80 °C for 2 h.

4 Electrical tests

4.1 Tests methods

Reliability and safety are the two most critical parameters of any EED. They should be safe and reliable to produce the required results. Safety is ensured during all stages of design, manufacturing and by preparing the composition to pass the required safety tests in order to ensure safe operation, handling, transportation and storage as per the requirements. The required minimum electrical energy to initiate a squib is just sufficient to raise the temperature of a bridge wire for ignition of the explosive composition. The bridge wire is in contact with this composition.

The Bruceton stair case method is widely used to calculate the all fire current (AFC) and no fire current (NFC) of the EED [20-23]. The energy of the EED is determined by the I^2Rt formula. The energy estimation of an EED for these two cases are minimum All Fire Current (AFC) and maximum No Fire Current (NFC).

The energy is received by the squib wire and converted into heat energy; the temperature of a squib increases. The source of energy, the squib, gives in time t, the energy ($P \cdot t$) to the squib. If I is the current flowing continuously through the circuit, the heat produced in the squib in time t will be – using energy formula – energy (E) equals:

$$E = P \cdot t = V \cdot I \cdot t \tag{15}$$

where P is power (W), I is current (A) and t is time (s).

According to Ohm's law, as $V = I \cdot R$:

$$E = I^2 \cdot R \cdot t \tag{16}$$

where R is resistance (Ω).

4.2 AFC tests

The minimum applied current for which the 'probability of squib firing' is 99.9% will always ensure the firing of EEDs. This was determined by the Bruceton method. The value of the AFC for the EED is 600 mA. For functioning of EEDs, there is certain value of firing current above which all EEDs should function without any failures. The AFC is a vital factor as it contributes to deliver this power or energy to the system over the specified life cycle. If the power is very high then the bridge heats very quickly to t_i and there is very little time for heat to be dispersed to the surrounding material (*t* is very small). All the energy then goes into heating the bridge. This represents a minimum energy condition to fire the initiator [24], *i.e.* $I = 600$ mA and $R = 2\ \Omega$ (average of 1.5 to 2.5 Ω). The average value is taken based on two extreme limits ($t = 10$ ms). As the current is supplied, the bridge fires on a millisecond timescale. All Fire Energy equals $0.6 \cdot 0.6 \cdot 2 \cdot 10 = 7.2$ mJ.

4.3 NFC tests

In the NFC test, the maximum current that can be applied at which the probability of 'EED not firing' is 99.9%. It was determined by the Bruceton method. NFC is important as a measure of the energy or power that, if inadvertently induced in a firing circuit, may cause un-commanded initiation of the EED. The current $I = 180$ mA, $R = 2\ \Omega$ and $t = 5$ s are obtained from the experiments. No Fire Energy equals $0.18 \cdot 0.18 \cdot 2 \cdot 5 = 0.324$ J.

No matter how high the power, if less energy is delivered than this amount (*t* is too short) then the bridge will never ignite and not fire. On the other hand if the power is very low there is sufficient time for the heat to be lost to the surroundings. If the heat transfer losses dominate, then no matter how long the power is applied for or how much energy is delivered, the bridge will never reach the ignition temperature and the device will not fire. By changing the material, length, diameter of the bridge wire, or method of application of explosive material or the composition, the activation level of an EED can be varied over a limited range. This helps the designer to select "no fire current" and "all fire current" levels to meet circuit requirements.

The firing current is one of the crucial characteristics of an EED which gives information about safe handling during storage and transportation and high confidence of firing in the mission mode. The current *vs.* time parameters are plotted. AFC and NFC range for EED is shown in Figure 5.

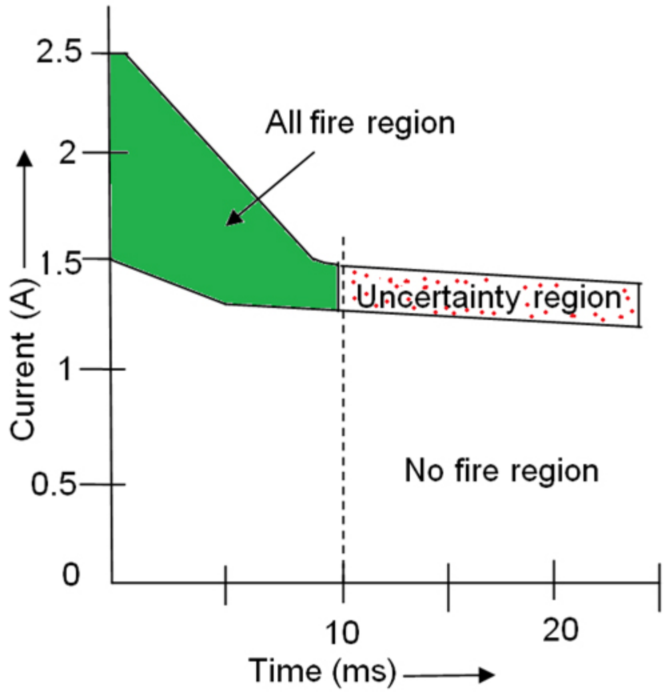


Figure 5. AFC and NFC range of EED

4.4 EED assembly into the cartridge and functionality test in closed vessel (CV)

The EED is assembled in the cavity of a main cartridge body as follows: the pyro composition is put into the cartridge body, then the main propellant charge and finally the case is turned over by placing the aluminium foil and rubber washer. The maximum pressure and rise time to reach maximum pressure of the cartridge was recorded in CV. The CV volume selection totally depends upon the particular application [25]. In this research, the CV volume is 150 cm^3 for conducting functionality tests. A pressure transducer with data acquisition system was used for measurement of these parameters.

4.5 Resistance tests

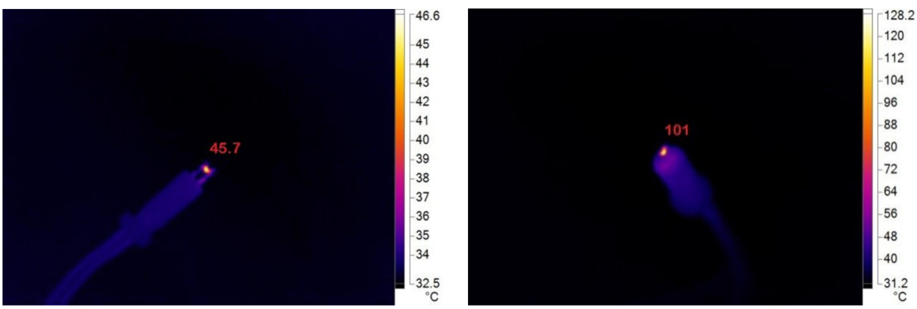
The EEDs resistances are measured using a safety Ohm-meter whose measuring current is less than 10 mA. It depends on the material diameter and length of bridge wire. The resistance range lies between 1.5 to 2.5 Ω.

4.6 Bridge Wire Temperature Measurement

The bridge wire temperature is measured using an infra-red thermal analyser by increasing the input current from 0.1 to 0.5 A. The DC current is regulated using GS610 source measuring unit. The experimental arrangement is illustrated in Figure 6. The temperature of the middle part of EED is higher than either end of the bridge.

Figure 6. Experimental arrangement for measuring the bridge wire temperature

After the electrical pulse, the thermal state of the bridge wire was obtained using a Fluke IR thermal camera. This shows different temperatures at varying current. Figures 7(a) to 7(f) shows the different temperature stages of squib wire at different current levels.



(a) (b)

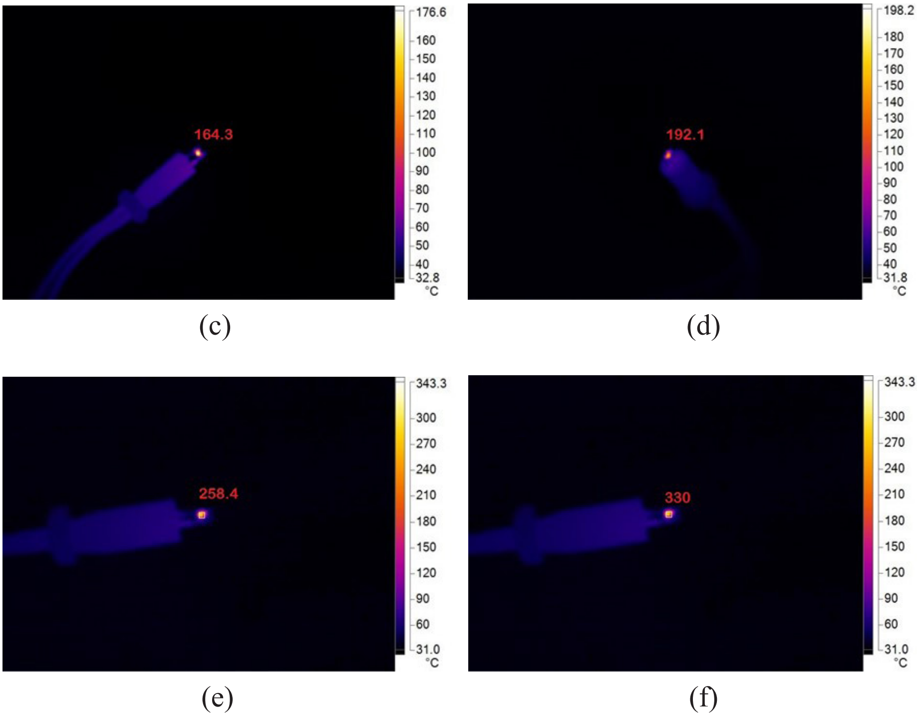


Figure 7. The different temperature stages of squib wire at different current levels: 0.2 (a), 0.4 (b), 0.455 (c), 0.462 (d), 0.478 (e) and 0.5 A (f)

5 Data Analysis of Results

All objects with a temperature above absolute zero emit infrared radiation energy to the surroundings. The wavelength distribution and infrared radiation energy of the object are related to the surface temperature. Therefore, by measuring the infrared radiation of the object itself, it is possible to accurately determine the surface temperature, which is infrared radiation based on the objective basis of temperature measurement. The voltage 24 V and time 5 s is taken into account for energy calculation. One of the standard pressure-time graph and ignition delay showing definite current pattern is illustrated in Figure 8.

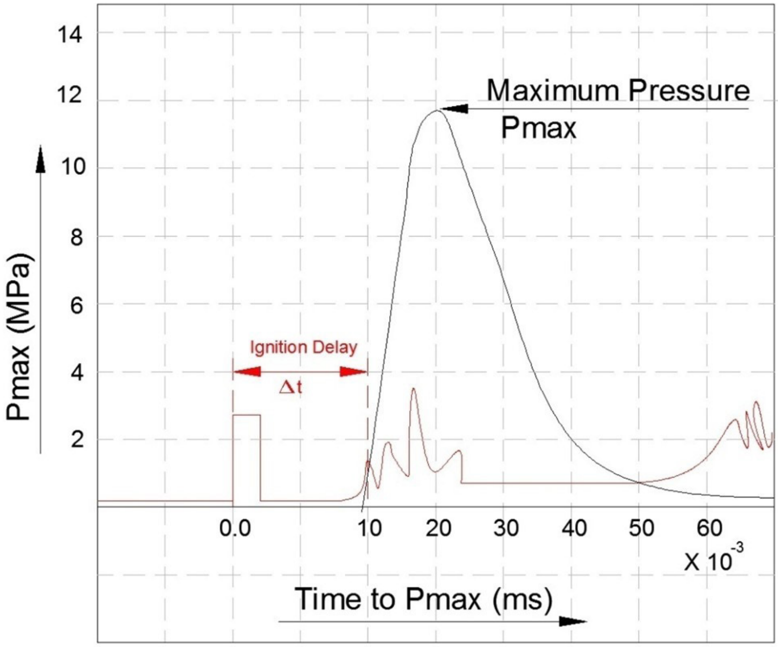


Figure 8. Standard pressure-time graph and ignition delay showing definite current pattern

The input current values of the bridge wire that were varied so as to obtain electrical energy are presented in Table 2. From this table, it is observed that the energy of the bridge wire varied from 70.64 to 119.56 mJ. This electrical energy is determined using Equation 16 as given in paragraph 4 above.

Table 2. Electrical energy at different current level

Sl. No.	Input current, I [A]	Resistance [Ω]	Δt [ms]	Electrical energy [mJ]
1	1.21	2.5	19.3	70.64
2	1.36	2.1	18.2	70.69
3	1.83	2	16.1	107.83
4	2	1.9	15.3	116.28
5	2.21	1.8	13.6	119.56
6	2.45	1.76	10.2	107.75
7	2.63	1.7	8.73	102.65
8	2.81	1.65	6.5	84.68
9	2.95	1.6	4.32	60.15
10	3.1	1.5	3.45	49.73

6 Discussions of Results

6.1 Example calculations results

The equations presented above were solved numerically. The example results with the following parameters. Volume (V) of the material is expressed as, Area (A) × length (l).

The non dimensional factor (hl/k) is known as the Biot number (B_i). This represents the ratio of internal (conduction) resistance to the surface (convection) resistance. The heat transfer coefficient in air (h) = 25 W/m^2-deg, length (l) = 0.033 · 10^{-3} m and k = 11.3 W/m-deg, B_i = 0.07 · 10^{-3} which is less than 0.1. The internal temperature gradients are small or the squib wire has a small internal (conduction) resistance. This means that the conduction resistance is less important. The squib wire is approximated as isothermal. The temperature in this process is uniform at a given time. The convective resistance then predominates and the transient phenomenon is controlled by convective heat exchange. Therefore a lumped capacitance analysis is performed for the squib bridge wire. As the energy at any given time is function of temperature. The total heat capacity is treated as one lump. This leads to uniform temperature throughout the body, so heat transfer is a function of time only and not of any space co-ordinate. The lumped parameter solution for transient conduction is applied. Taking t_a = 28 °C, t_i = 330 °C and t = 180 °C. Temperature 180 °C is taken as lead styphnate ignited at this temperature. Therefore this gives $\theta = (180 - 28) = 152$, $\theta_i = (330 - 28) = 302$ and $h/\rho VC = 0.205$. Substituting all these values in Equation 12, the time taken to reach the temperature of 330 °C is calculated t = 3.35 s.

Table 2 shows that as input current increases the energy increases and the temperature of the squib also increases keeping voltage constant. Figure 5 shows the temperature distribution within the bridge wire-pyrotechnic. A number of important points can be demonstrated with this figure. First, the discontinuity in temperature at the bridge wire – pyrotechnic interface is quite apparent. Second, there is very little temperature difference between the centre of the bridge wire and the outside surface of the bridge wire. When the current level reaches 0.5 A the maximum temperature of the bridge wire is 330 °C. At this temperature, the composition undergoes detonation accompanied by high pressure and temperature (>2000 °C) where the bridge wire melts and breaks. Before reaching this final temperature, the pyrotechnic composition initiates. The minimum and maximum energy is calculated as 0.324 J and 7.2 J, respectively. B_i = 0.07 · 10^{-3} which is much less than 0.1, indicates that the internal temperature gradients are small. Therefore lumped parameter analysis is applicable. A time constant 3.35 s has been determined using the lumped parameters.

The total electrical energy delivered to the bridge wire is I^2Rt, and the energy received by the pyrotechnic is the instantaneous heat flux out of the bridge wire integrated over time.

7 Summary

From the analysis it was concluded that, the effort described in this paper has shown promising results using a mathematical model of lumped analysis for the squib. The EED also qualified and passed all the required safety tests and is recommended for use in power cartridges for water-jet application after all experimental trials. The mathematical model presented here may be successfully applied in determining the various electrical parameters for EEDs. The energy of the bridge wire varies from 49.73 to 119.56 mJ. This article experimentally and theoretically discussed the lumped parameters analysis of EED and the determination of various electrical characteristics.

From the above deliberations, the following inferences can be drawn:

- The minimum and maximum energy of the EED are 49.73 and 119.56 mJ, respectively.
- The AFC and NFC of EED are 7.2 mJ and 0.324 J, respectively.
- A time constant 3.35 s has been determined using the lump parameters to reach the temperature of 330 °C.
- Biot number (B_i) for the squib is $0.07 \cdot 10^{-3}$.

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