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VARIATION IN ENHANCED GAS GENERATION RATES IN ELECTROTHERMAL-CHEMICAL CLOSED CHAMBER STUDIES

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This paper describes experimental investigations of the apparent variation in enhanced gas generation rates in recent electrothermal-chemical closed vessel studies. This enhancement is noted when electrical energy in the form of plasma is discharged into pressurised burning propellant. The analysis used to calculate the burn rates is based upon Vieille's Law of burning. Two studies are reported in detail here. The first investigates the effects of plasma composition and the second that of electrical discharge power and propellant composition upon the calculated enhancement levels. A summary of the closed vessel analytical techniques used and some suggestions to explain the phenomena are given.

INTRODUCTION

The UK Defence Evaluation and Research Agency (DERA) is investigating a number of different electrothermal-chemical (ETC) gun concepts that utilise solid propellants. One prime area of interest is the apparent alteration to Vieille's Law as a consequence of the introduction of electrical energy in the form of plasma into the ballistic cycle of a gun. The apparent enhanced gas generation rate (EGGR) of propellants has been reported by a number of researchers for many years [1,2,3] but the exact nature of the plasma propellant interaction still remains elusive. EGGR levels have been differentiated for enhancement 'during electrical discharge' (EGGRDED) and 'post electrical discharge' (PEDEGGR) from transient pressure records of closed bomb tests [4]. From a control perspective, it is more desirable to have a propellant exhibit a high level of EGGRDED than a high level of PEDEGGR. However, a high level of PEDEGGR would allow improved performance with a minimal use of electrical energy.

This paper describes two sets of ETC experimentation conducted within a 400 cm^3 closed chamber. The first set explores a number of different plasma compositions to determine whether the EGGR levels can be affected catalytically. The second set explores the enhancement values as a function of electrical discharge power when used with various propellants including high energy, low vulnerability ammunition (HELOVA) propellant compositions. The hypothesised existence of a plasma electrical power threshold value for PEDEGGR is also explored [5].

STANDARD EGGR TESTING

In standard EGGR tests, around 49 g of propellant is ignited conventionally with a Gevelot primer igniter aided by 1 g of gunpowder. Around 26 kJ of electrical energy in the form of an electrical plasma is then added with a peak power of around 60 MW, discharged in around 0.8 ms from a capacitor based pulse forming network [6]. The electrical energy is discharged into the combustion chamber at around 35 MPa through two electrodes initially connected by a 20 mm length of (usually) 0.7 mm diameter fuse wire. The fuse wire and electrode materials, mixed with propellant gases, form the plasma. Such direct introduction of electrical energy is known as 'current injection' (C.I.) as opposed to other discharge options such as offered by capillary plasma generators [7].

GAS GENERATION RATE ANALYSIS

The way in which the propellant characteristics change during the combustion cycle can be studied in closed vessel experiments. The pressure in the chamber is measured as a function of time (with for example piezo-electric pressure transducers) and isobaric conditions are assumed to prevail. The pressurisation *P(t)* and rate of increase in mass of gas, *dm/dt* within a closed bomb chamber during the combustion of solid propellant can be related by a semi-empirical law expressed as:

$$P(t) = F\int_0^t (1/V_0)\frac{dm}{dt}dt = F\rho\int_0^t (1/V_0)S\beta P^{\alpha}dt \qquad (1)$$

where
F is known as the force constant of the propellant
V_0 is the free volume of the chamber at time t
ρ is the density of the solid propellant
S is the burning surface area at time t
β is a constant known as the burn rate coefficient of the propellant and
α is known as the burn rate pressure index of the propellant.

As the propellant changes phase the volume of the chamber reduces slightly due to the effective space taken up by the propellant gas phase molecules being greater than that of the propellant solid phase molecules.

βP^{α} is often referred to as the propellant burn rate, *r* and is directly proportional to the rate of change of pressure within the chamber if all else remains constant. Plots of *dP/dt* or βP^{α} (i.e. the burn rate, *r*) against *P* will give an approximate straight-line relationship for α close to unity, reasonably constant S and V_0 and allowances for heat loss. This is known as Vieille's Law of burning. The introduction of electrical energy is found to cause

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a deviation away from Vieille's Law during the discharge and post discharge with some compositions.

Closed chamber gas generation rate analysis [4] was conducted for each test performed in both sets of experiments reported here, using the transient pressure records from two co-planar calibrated piezo-electric pressure transducers. Analysis is conducted using a code called BRLCB [8]. This code attempts to take account of the thermal effects of any electrical discharge. The code assumes that the propellant burns in parallel layers and cannot distinguish between possible causes of deduced EGGR. Previous studies [4,5] have portrayed the variation in gas generation rates during and post electrical discharge as a variation in the propellant burn rate coefficient. In the analysis, the burn rate coefficient profile is integrated with respect to pressure over the appropriate pressure range during or post electrical discharge. The integrated burn rate coefficient is then divided by the pressure difference of the range to determine a pressure-averaged burn rate coefficient over the appropriate pressure range. The resultant mean burn rate coefficients are then divided by those from baseline tests where no electrical energy was discharged. This determines a unitless quantity that indicates the level of enhancement in the burn-rate coefficient. These are the quantitative definition of the EGGRDED and PEDEGGR levels. A level value of two indicates that the average burn rate coefficient over that pressure range is twice that of a conventional burn rate coefficient.

EXPERIMENT 1 – THE EFFECT OF PLASMA COMPOSITION ON EGGR

Standard EGGR tests were conducted using different fuse wire and electrode materials. Copper, tinned copper, nickel, aluminium, carbon and steel fuse wires, 0.5 mm or 0.7 mm diameter, were used with copper, copper, nickel, aluminium, carbon and steel electrodes respectively. A sensitive double based nitro-cellulose and nitro-glycerine RDX enriched propellant, composition X, was used. Twenty sticks 60 mm long were carefully loaded in the same fashion for each test. Two baseline tests and several nominally identical electrical tests were carried out for each wire/electrode composition. Fig. 1 shows the resulting pressure-time records from a full set of tests from one plasma composition (two baselines and a number of nominally identical electrical tests). The ignition delay (i.e. the time for the pressure to attain some defined value) was very variable and so each record has been time-shifted so as to overlay in the early part of their pressure histories.

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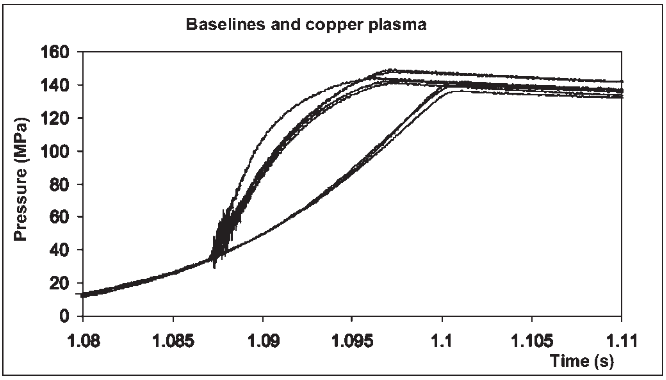

FIGURE 1

The large random variability determined for EGGRDED and PEDEGGR between supposedly identical electrical tests, obvious from plots such as shown in Fig. 1, was disconcerting. Ideally, a larger number of tests would have been fired. This being cost prohibitive, any potential difference between the materials is somewhat obscured by the large data scatter. However, certain statistical methods have been employed which take into account the large degree of variability and the limited data set. The first method employed was used to determine the nature of the variability. The entire electrical test data set was used to produce a 'normal probability plot'. This is achieved by sorting the enhancement values into ascending order and estimating the percentage population probabilities below each value using statistical tables. When the values and the percentage probabilities are plotted onto normal probability graph paper, a normal distribution in variability is concluded if the points lay along a reasonable straight line. For these tests a normally distributed variability indicated that the cause(s) of variability were random.

With such a small sample size for each group, further analysis would be unsafe without somehow increasing the sample size to increase the degrees of freedom and reduce the standard deviation. Because the variability is random, the standard deviations for EGGRDED levels can be combined from the entire wire/electrode composition data-set, as can those of PEDEGGR; this was done and served to increase the degrees of freedom and reduce the standard deviation making further statistical analysis safer. The next stage in the analysis was to calculate the true mean of EGGRDED and PEDEGGR for each wire/electrode composition to a significance level of 5 % (the range of values for which one can be 95 % certain the mean will lie within). Fig. 2 and Fig. 3 shows the results of such analysis for EGGRDED and PEDEGGR respectively. As can be seen, there seems to be a small difference between the means, but there is some overlap between the ranges.

Further statistical analysis shows that there is no difference at the 5% significance level (with 23 degrees of freedom) between any of the EGGR averages except for copper and steel. These show a difference until the 2% significance level is reached for EGGRDED and a difference between the pure copper and the steel for PEDEGGR at 5%.

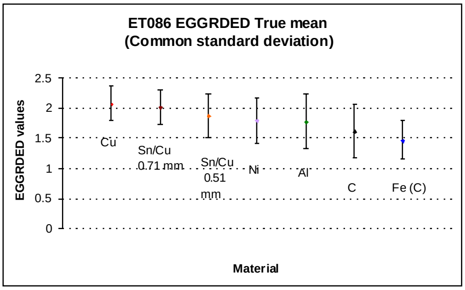

FIGURE 2

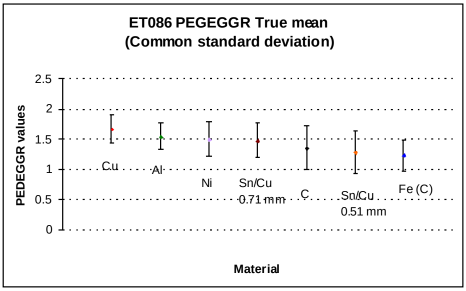

FIGURE 3

These small differences between the averages would probably vanish if the small variation between the two pressure gauges were taken into account: an increase in the variation would further spread the true mean ranges. Thus, the conclusion is that there appears to be some small difference between the mean values for EGGRDED and PEDEGGR for different materials, but this difference can be accounted for by random variations within the entire data set. These variations may be due to the experimental set-up conditions that were not controlled or known: e.g. the position of the propellant at the moment of electrical discharge, the condition of the wire at the moment of electrical discharge and the behaviour of the discharge itself within the test vessel.

EXPERIMENT 2 – THE EFFECT OF DISCHARGE POWER ON EGGR

Previous work [4,5] has suggested a PEDEGGR power threshold may exist for propellants, whereby enhancement would only occur after a certain value of discharged electrical power. A single based HMX poly NIMMO enriched propellant and two single based nitro-cellulose and RDX enriched HELOVA propellant compositions, known as L1, L2 and L3 respectively, together with composition X were investigated using the standard EGGR test set-up for threshold values. The electrical energy of these tests was varied but the period of the discharged remained fixed at around 0.8 ms, and a 0.7 mm tinned copper fuse wire was used for each test. Analysis of the EGGRDED and PEDEGGR values was carried out for each propellant composition at each electrical power level. A modified burn rate law relating directly to electrical power is defined here:

$$r = \beta P^{\alpha}\,(1 + (p_{peak} - T)\,\Psi) = \beta P^{\alpha}\,\varepsilon \qquad (2)$$

where
T is the enhancement threshold power, which is the subject of this work
p_{peak} is the average discharge power
Ψ is the enhancement power density value (no enhancement is inferred with a value $\Psi = 0$)
and
ε is the EGGRDED or PEDEGGR enhancement level value.

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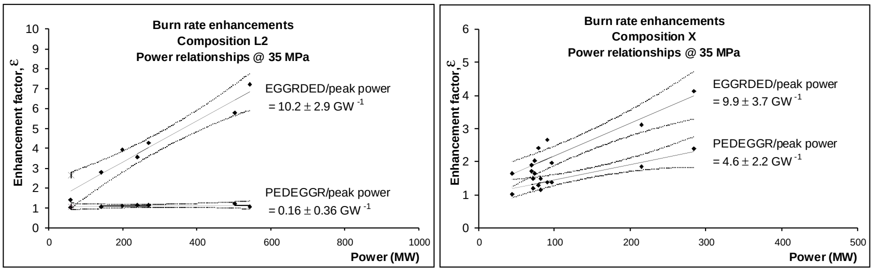

FIGURE 4

Fig. 4 shows the deduced values ε for various power levels for two of the propellant compositions. The curved confidence bands represent the 95 % confidence interval for the regression statistics employed. Fig. 5 shows a summary of the enhancement power density values for each propellant composition. The regression line gradients from plots such as Fig. 4 give the data points in Fig. 5 and the confidence bands give the error bars. It is clear from Fig. 5 that the EGGRDED power density values are composition independent but PEDEGGR values are composition dependent, with those propellants showing PEDEGGR having a value of T = 0 (e.g. composition X in Fig. 4); there are no threshold values. The 'all propellants' EGGRDED value is that from treating all the EGGRDED enhancement factors from the different compositions together as one group. This represents a data set of thirty and the error bars are probably representative of the true variability in EGGRDED, given that the effect is propellant composition independent.

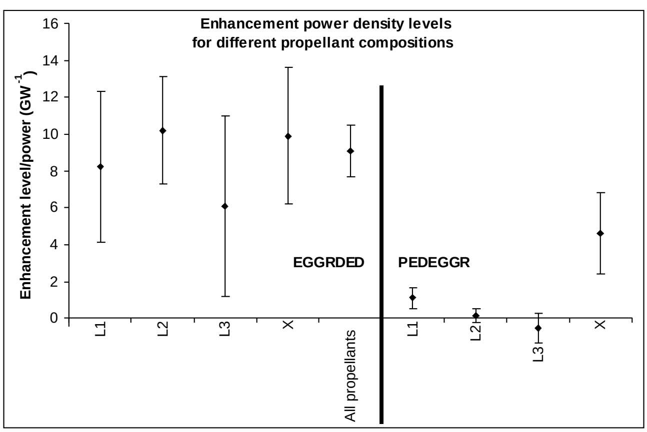

FIGURE 5

DISCUSSION

That EGGRDED is propellant composition independent and PEDEGGR is composition dependent shows that it is correct to separate the two in ETC EGGR analysis. This may be particularly important in high power, long duration discharge pulses where EGGRDED and PEDEGGR effects may occur simultaneously. The question as to when

PEDEGGR begins during the discharge cannot be readily answered until the mechanisms involved in EGGRDED and PEDEGGR are better understood. There are a number of possible mechanisms for each enhancement. One possibility is a change in the burn-rate pressure index and/or coefficient; these may be due to changes in heat transfer to the grain surface, sub-surface heating or gas phase chemical kinetics. Plasma heat transfer mechanisms during the discharge are as yet poorly understood, and work is in hand at DERA to try to rectify this. Other possibilities include erosive burning and propellant break-up and other surface area increase mechanisms occurring during the discharge. Further, as yet unexplored causes may exist. The authors have carried out some work, showing that volume changes due to plasma incompressibility proportional to the discharge power can account for the EGGRDED effect, although this is sensitive to the accuracy of the plasma equation of state used. This work suggested that, for these tests, incompressible plasma occupies a volume of around 10 % of the chamber at peak power.

Indeed, it might well be shown that different types of plasma generator give rise to similar effects but for different reasons. Solid JA2 propellant ETC experiments reported by different groups have given varied results, with evidence of PEDEGGR reported by some [9] and not by others [10]. Interesting phenomenon have been observed with interrupted JA2 burn tests both with an opaque composition containing graphite [9] and a translucent composition without graphite [11,12]. Fundamental research at DERA continues to explore the EGGR phenomenon with in-grain spectroscopy and the development of an optical fibre method to measure the burn-rate directly under closed chamber dynamic conditions, as well as propellant chemical kinetics code development.

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