STUDIES OF IGNITION DELAY AT 40 mm CALIBRE

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Research is being undertaken into ignition delay using black powder to ignite a double based and a CAB based 'LOVA' gun propellant at 40 mm calibre. A high performance igniter is used in the study with the mass of black powder varied in order to map out the ignition delay as a function of igniter energy of both these propellant compositions. The study includes altering the propellant loading density of both compositions. The purpose of the study is to improve the predictive modelling capability for ignition, including ignition delay, which is considered an important and sensitive measurand for ignition. This paper details and discusses results to date.

INTRODUCTION

The ignition phenomenon is a poorly understood area of the internal ballistics process. This position is widely accepted. The UK, along with France and Germany, is participating in a EUROPA Technical Arrangement on Ignition Phenomena. In this programme the UK is mainly concentrating on the study of conventional ignition of solid gun propellants; French and German institutes are mainly concentrating on plasma ignition. The purpose of this programme is to improve the predictive modelling capability for ignition, including ignition delay which is considered an important and sensitive measurand. This paper details the aims and results of one experimental study conducted for the UK EUROPA ignition programme.

The study of ignition is being mainly driven by the requirement for insensitive munitions (IM). Advanced, insensitive, low vulnerability ammunition (LOVA) charges will be required in future gun propulsion applications and it is generally perceived that these will present difficult ignition conditions. Current LOVAs, such as featured in this paper, can be ignited with black powder but require increased effort to do so. The next generation charges may pose such an ignition problem that current ignition technology will be inadequate. In the UK for example, promising advanced IM charges have been developed in the past but then disregarded due to their extreme ignition characteristics (they were unignitable with black powder). Thus, prior to the development of the such charges it is important to more fully understand the ignition phenomena in order to develop advanced igniter concepts in a timely and cost effective manner.

IGNITION STUDIES EXPERIMENTAL SET-UP

As part of the UK programme, a research study has been undertaken into ignition delay using black powder to ignite both NK1280, a double based gun propellant and NL008, a cellulose acetate butyrate (CAB) based 'LOVA' gun propellant at 40 mm calibre. Both compositions were provided by EURENCO in Sweden. A modified 'Bofors' high performance igniter was used in the study [1]. This igniter comprises a 20 cm^3 volume high-pressure chamber located within the breech of a gun. This high-pressure chamber was filled with a variable mass (from around 2 to 10 g) of black powder and sealed with a thin metal 'burst disc'. A piccolo-type igniter tube was fixed to the nozzle of the high-pressure chamber. During the tests, a small electric squib igniter was used to ignite the black powder which combusted under closed-vessel conditions. At a certain pressure [1] the burst disc ruptured and the burning black powder particulates and combustion gases vented along the piccolo tube and out into the gun chamber through perforations along the length of the tube.

This igniter system was used to ignite a propellant charge located within the gun chamber. The propellant charge was carefully built around the igniter and held securely by plastic netting. The loading density of the propellant was varied between 0.2 and 0.54 g cm^{-3} by changing the radius of the charge – the charge length was maintained at the full length of the igniter piccolo tube so as to maximise the energy transfer from the igniter material.

Pressures were measured within the high pressure chamber and at several locations within the gun chamber.

IGNITION DELAY VERSUS IGNITER ENERGY RELATIONSHIP

The mass of black powder used for ignition was varied in order to map out the ignition delay of the two propellant compositions under varying loading conditions. It was predicted that the ignition delay, t_i would be related to the energy (mass) of the black powder by a power law of the form:

$$t_i = a\,(\varepsilon - \varepsilon_\infty)^b \tag{1}$$

where:

a and b are constants,

ε is the energy in the black powder (directly proportional to the mass) and

ε_∞ is the energy which just gives a mis-fire ($t_i = \infty$).

It is recognised that ε is not necessarily all transferred to the propellant: some of the energy is used to heat the piccolo tube for example.

The relationship in Equation (1) is based upon a previous study into ignition delay at large calibre using electrothermal plasma ignition (ETI). Figure 1 shows this relationship, plotted on a log-log scale, with coefficients a = 817, b = - 1.2 and ε_∞ = 17.5 kJ. These values were found by changing ε_∞ to maximise the correlation coefficient (R^2). The mis-fire energy, ε_∞ was not experimentally validated. A small range of charge and capillary plasma generator designs were used over a number of years for this study.

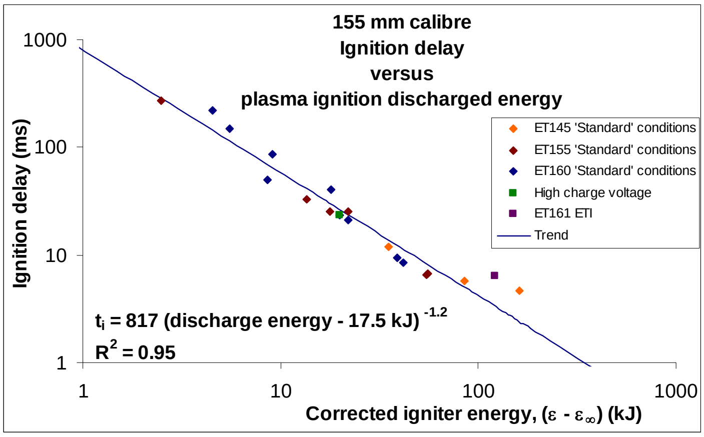

FIGURE 1. Ignition delay as a function of energy for 155 mm calibre ETI

DEFINITION OF IGNITION DELAY

Great care must be taken over the definition of ignition delay. For the work shown in Figure 1, ignition delay was defined as the time from the start of the generation of the plasma until a pressure of 5 MPa was attained in the gun chamber. For the current study, the ignition train is relatively complex and each stage has some variation associated with it. Hence, for the start of ignition, the rupture of the burst disc, which gives a clear signal on the pressure trace recorded both within the high pressure chamber and the gun chamber, will be used. Furthermore, this is the last stage in the ignition train prior to the igniter material interacting with the gun propellant and so lends itself nicely to this particular study. Defining the end of the ignition delay is more difficult. The traditional method of defining a pressure above that generated by the igniter itself is not adequate here because the rate of rise of pressure from the combusting gun propellant is a function of loading density, which is being varied. This would introduce variability in the recorded ignition delay as a function of loading density, with higher loading densities giving shorter ignition delays as measured by this method. Thus, a more subtle approach was required.

To accurately determine the end of the ignition delay, a set of tests were conducted discharging the igniter into an inert propellant simulant. Pressure-time curves from the inert tests for a set of black powder masses were compared to those from energetic propellant tests and the moment the two curves diverged was taken as an indication that propellant burning had begun and the ignition sequence ended. Great care was taken to make the comparison between the inert and energetic tests as fair as possible; the free volume of the chamber was carefully controlled, and the inert propellant simulant's thermal and geometrical characteristics closely matched those of the real gun propellant. Industrial polycarbonate granules were used. Figure 2 shows an example of this process with the chamber pressures generated for 6 g of black powder discharged into 94 g of inert grains and 118 g of NL008 propellant (the mass difference signifies the differences in density between the inert and energetic propellant). The free volume within the chamber was 534 cm^3 in both cases.

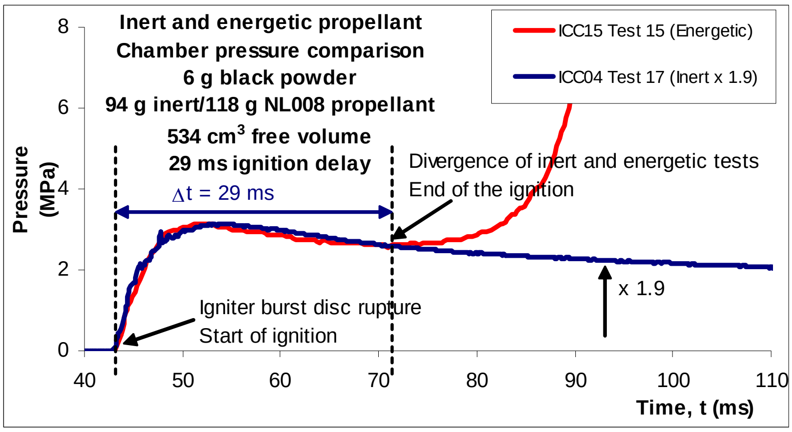

FIGURE 2. Chamber pressure of an inert propellant simulant compared with energetic propellant – short ignition delay

The burst disc ruptures at around 43 ms into the test (the time axis of the inert test has been shifted to coincide with this event). Both curves coincide for 29 ms until at 72 ms into the test, the two curves diverge. This divergence defines the end of ignition with an ignition delay, Δt of 29 ms in this case.

To get the pressure match shown in Figure 2, the pressure measured during the inert tests had to be multiplied by a correction factor of 1.9. It was found that this was fairly constant for several NL008 tests conducted at a range of loading densities. When NK1280 propellant was tested under similar conditions, the correction factor was 1.35. It is easy to suppose this difference was due to differences in heat loss. However, the small differences in thermal properties between the propellant could not account for the large difference correction factors. It was concluded that mechanical erosion (ablation) of propellant may have been occurring during the discharge of the igniter, with the high-velocity combustion products vaporising the surface of grains very close to the perforations in the piccolo tube and adding to the chamber pressure. Then, physical differences between the two propellants (e.g. with NL008 being softer than NK1280) would account for differences in ablation rates. No ablation was noticed on recovered inert grains. Further tests will be required to fully understand this event. It is important because the assumption that the energy available for ignition is that of the black powder alone may be erroneous – extra energy is supplied from the vaporised (and presumably combusted) propellant.

A second way to look at the definition of ignition delay was required for extended ignition delays (of several seconds). Under these circumstances, the comparison with an inert propellant simulant was found untrustworthy. Whereas the pressure for the inert tests simply decayed as the combustion products cooled, the pressure generated for the energetic propellant tests initially reduced but then stabilised to a plateau level of around 0.5 – 0.7 MPa before finally increasing as combustion took hold. With these tests, the moment a change in gradient (dp/dt) occurred after the plateau stage was taken as the end of the ignition delay. This is shown in Figure 3.

Looking again at Figure 2, the moment of divergence between the inert and energetic propellant tests also corresponds with a change in dp/dt, so there is no difference between these two definitions for the end of ignition delay.

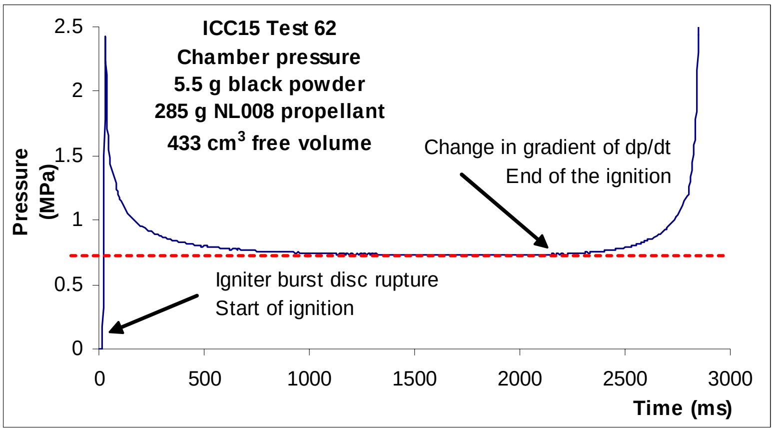

FIGURE 3. Chamber pressure of energetic propellant – extended ignition delay

IGNITION DELAY RESULTS

Figure 4 shows the 40 mm calibre ignition delay as a function of black powder mass (proportional to energy) for the double based (NK1280) and a CAB based (NL008) gun propellant on a linear-log plot. The function shown in Equation (1) has been fitted to the data for both compositions. The functions were determined using experimentally derived values of m_∞ followed by a solving process to maximise the correlation coefficients.

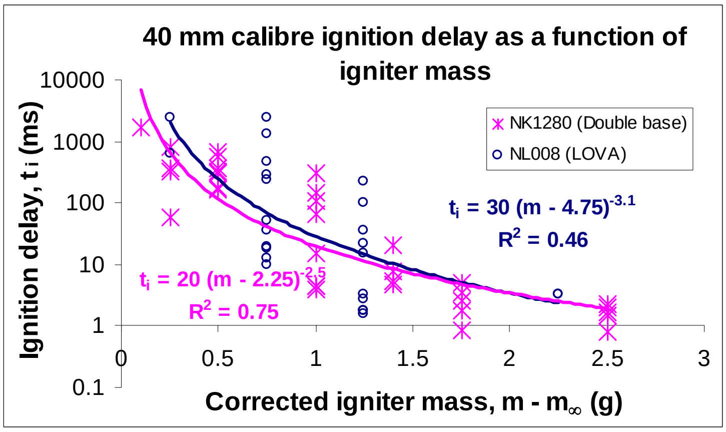

FIGURE 4. Ignition delay as a function of igniter mass (proportional to energy) for 40 mm calibre black powder ignition

The first point to be drawn from Figure 4 is that, for any given ignition delay, around twice the mass (energy) of black powder is required to ignite the LOVA (> 4.75 g) as for the double based propellant (> 2.25 g). This is in good agreement with the results from an earlier US study which suggests a LOVA is in general between two and three times more difficult to ignite. One might expect the LOVA composition to be more difficult to ignite than the double based composition due to its inherent decreased sensitivity but also from the findings of earlier studies. However, what is most interesting and unexpected is the similarity between the value of the coefficients *a* and *b* for the functions for NK1280 and NL008: the gradient of the curves are surprisingly similar. The gradient appears to be a function of the igniter system rather than propellant composition for a given calibre. There is no immediately obvious reason to expect this.

Finally, the variability in the data is such that it could be questioned whether Equation (1) applies to this data-set at all; the correlation coefficient for NK1280 is 0.75 and that for NL008 is 0.46.

Figure 4 is the combined result for several loading densities and so one explanation for this high variability might be thought to be that loading density plays a significant part in ignition delay. However, close inspection of the results shows that there is no significant relationship between loading density and ignition delay. If there is any relationship then it is small and lost in the scatter of the data. Figure 5 shows the results (on a log-log plot) of a reduced data set from similar loading density tests with a chamber free volume of 484 cm^3 which removes any confusion loading density may introduce. Each function's coefficients have slightly altered and the variability has reduced but only because of the reduction in the data set.

The results shown in Figure 4 are in the process of being subjected to modelling.

The large difference between the two propellant compositions, plus the similarity in their power law coefficients and lack of any significant difference for loading density are useful for this process. However, the significant degree of variability and the length of some of the ignition delays present considerable challenges to the modelling effort.

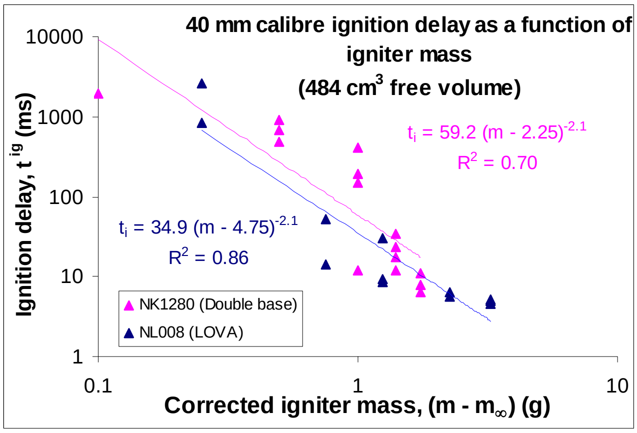

FIGURE 5. Ignition delay as a function of igniter mass (proportional to energy) for 40 mm calibre black powder ignition for a given propellant loading density

DISCUSSION

In marked contrast to the good correlation found between ignition delay and electrothermal plasma energy, the correlation using black powder is unreasonably poor – as low as 0.46 for NL008 (Figure 4). There are two possible explanations for this: (i) the variability in ignition delay is calibre-specific, with a greater degree of variability associated with small calibres or (ii) that black powder has a low and/or variable rate of energy transfer (i.e. poor energy transfer efficiency) with respect to ETI.

The first explanation could be understood in terms of turbulent flow within the igniter axial tube. For the 40 mm calibre tests, the tube diameter was around 6 mm whereas for the 155 mm calibre tests, the diameter was around 42 mm. Highly turbulent conditions are expected within the smaller diameter tube. The performance of the high-pressure chamber in the conventional igniter has been measured and found to be highly repeatable [1] and there is no correlation between small variations, for example in the rupture pressure of the burst disc, and the ignition delay variability. Measurement of the pressure of the igniter within the piccolo tube does, however, show some significant test-to-test variability. These measurements were only made during the inert propellant tests and so no correlation with ignition delay variability is possible.

The second explanation revolving around energy transfer efficiency is more fundamental and asserts that under *difficult* ignition conditions, black powder performance is poor whereas electrothermal plasma performs well. This assertion is supported by several published and unpublished pieces of work where some effort has been made to show the ignition of conventional igniters is less reproducible than for electrothermal plasma igniters [4, 5]. Furthermore, this may be why significant effort to optimise a conventional igniter has to be made for even small changes in charge design, whereas large variations in charge (from granular modular charges to high-loading density disc charges) have been ignited by a single plasma generator design with no optimisation. This latter point indicates that electrothermal igniters are inherently more robust and versatile devices having high utility.

In the work described in this paper, the igniter has been challenged by reducing the energy available for ignition. In charge design, the use of less sensitive propellants or higher loading densities offer challenging scenarios. If the assertion that under difficult ignition conditions, black powder performance is poor but electrothermal plasma performs well is correct, then this provides firm evidence for the benefits of ETI to ignite advanced, insensitive LOVA charges prior to their development.

Some work has been performed by TNO at 40 mm calibre showing that plasma ignition has better reproducibility than black powder ignition [5]. However, under the conditions used for the UK black powder study, it is conceivable that at 40 mm, plasma ignition may suffer from the same degree of ignition delay variability as this high-performance black powder igniter. Therefore, ETI experimentation is required at 40 mm to directly compare with this black powder study.

Little work has been performed to investigate the ignition delay variability of black powder for extended ignition delays for direct comparison with plasma ignition at 155 mm. Therefore, directly comparable ETI and black powder igniter tests are required at large calibre to complete this study.

SUMMARY AND CONCLUSIONS

A study at 40 mm calibre has been undertaken whereby the mass of black powder within a high-performance igniter has been varied during the ignition of two distinctly different gun propellants for the purpose of studying ignition delay. This work has been performed with the intention of validating ignition codes within internal ballistics models.

The results indicate that the ignition of propellant by black powder is dominated by a high degree of variability when ignition conditions are marginal. However, the results can be fitted to a power law. This law indicates that, in agreement with previous work, around twice the mass (energy) is required for less sensitive CAB based LOVA propellants than for double based compositions. Furthermore, the gradients (power law coefficients) appear to be a function of igniter system rather than propellant composition for a given calibre. There is no immediately obvious reason to expect this.

The results of this 40 mm calibre study have been compared with previous similar studies (at 155 mm calibre) using electrothermal plasma as an ignition source. Plasma ignition at 155 mm is shown to be highly predictable when using similar marginal ignition conditions. This finding can be explained in terms of either the calibre or the efficiency of the energy transfer process. Comparative studies using both 40 mm ETI and 155 mm conventional, and further ETI tests, are required in order to understand the processes more fully.

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This work was carried out as part of the Weapons and Platform Effectors Domain of the UK MOD Research Acquisition Organisation.