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# Ignition and combustion of pyrotechnics at low pressures and at temperature extremes

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ABSTRACT

Rapid and effective ignition of pyrotechnic countermeasure decoy flares is vitally important to the safety of expensive military platforms such as aircraft. QinetiQ is conducting experimental and theoretical research into pyrotechnic countermeasure decoy flares. A key part of this work is the development and application of improved models to increase the understanding of the ignition processes occurring for these flares. These models have been implemented in a two-dimensional computational model and details are described in this paper. Previous work has conducted experiments and validated the computational model at ambient temperature and pressure. More recently the computational model has been validated at pressures down to that equivalent to 40,000 feet but at ambient temperature (~290 K). This paper describes further experimental work in which the ignition delays of the priming material in inert countermeasure decoy flares were determined for pressures down to 40,000 feet and at temperature extremes of −40 °C and 100 °C. Also included in this paper is a comparison of the measured and predicted ignition delays at low pressures and temperature extremes. The agreement between the predicted and measured ignition delays is acceptable.



## 1. Introduction

Rapid and effective ignition of pyrotechnic countermeasure decoy flares is vitally important to the safety of expensive military platforms such as aircraft. Ignition needs to be rapid and consistent for the countermeasure to be effective. QinetiQ is conducting experimental and theoretical research into pyrotechnic countermeasure decoy flares. A key part of this work is the development and application of improved ignition models to improve the understanding of the ignition processes occurring for these flares. Typically, pyrotechnic countermeasure decoy flares are wrapped in a material such as foil. Until this material bursts or ruptures, the flare can be considered to be effectively a closed system. Therefore it is possible to use gun internal ballistics models to investigate the ignition and combustion processes in these flares.

Improved ignition models have been implemented in a two-dimensional (2D) gun internal ballistics code named QIMIBS (QinetiQ Modular Internal Ballistics Software) [13]. QIMIBS contains models of the convective, radiative, condensative and conductive heat transfer processes from the igniter combustion products to the main propellant, in this case the flare body. An intensive modelling work programme, closely supported by experiments to provide data for and to validate the modelling, was undertaken for a baseline pyrotechnic flare. The modelling investigated the main heat transfer processes to determine the dominant energy transfer modes and ways by which the ignition delay of the flares could be decreased.

Previous work has reported on the development, verification and validation of the heat transfer models embodied in QIMIBS [11]. This work has been conducted at 21 °C and at atmospheric pressure (0.1 MPa) only.

Further modelling work has been conducted using results from experiments conducted by Esterline in a high altitude chamber (HAC) [12] and by QinetiQ in a modified vacuum oven. The HAC is capable of reducing the ambient pressure to that equivalent to an altitude of 40,000 feet (12,192 m, 0.0188 MPa). Tests of inert pyrotechnic countermeasure decoy flare bodies containing a priming material were conducted in the HAC at pressures equivalent to sea level, 20,000 feet (6096 m, 0.0466 MPa) and 40,000 feet. The tests were recorded using a high speed video camera. The modified vacuum oven is capable of operating at pressures similar to those of the HAC and, in addition, at temperatures in the range -40-100 °C.

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QIMIBS was used to model these tests and to predict the ignition delay of the priming material. The QIMIBS predictions and measured data were in good agreement.

This paper reviews the models and energy transfer equations important to the requirement to model the ignition of energetic materials. It then describes the experiments and computer modelling carried out. Note that this paper concentrates on the ignition process of the priming material; hence inert flare bodies were used.

## 2. Ignition model

The ignition of an energetic material is a very complex process, involving many factors. Any ignition model should take into account the following factors:

- Thermal properties of the material to be ignited;
- Transport properties of the igniter gases;
- Convective, radiative, conductive and condensative heating of the material to be ignited;
- Melting of components;
- Latent heat of melting;
- Vaporisation of components;
- Latent heat of vaporisation;
- Subsurface chemical reactions – these can be endothermic or exothermic;
- Gas phase chemical reactions – these can also be endothermic or exothermic;
- Multi-phase flow.

To model all of these processes would require a substantial model development and validation process which is beyond the scope of available resources. Furthermore, although key chemical reaction steps in the ignition of some energetic materials are known, in general such information is not available in the open literature, if known at all. Even if such information was known and implemented in a computational code, the execution of it would take many hours and probably days, even on computer systems having parallel processors. Consequently, assumptions on the ignition process are usually made in order to develop a tractable "engineering" level computational model. It is accepted that such a computational model may not be capable of predicting ignition delays to a high degree of accuracy, but is sufficiently accurate to predict broad trends and to compare one ignition system or energetic material with others. Furthermore, such a computational model should be capable of predicting to an acceptable level of accuracy whether ignition will occur – the go/no-go criterion. This second approach has been used by QinetiQ in the UK to investigate and improve its understanding of the ignition of pyrotechnic countermeasure decoy flares. A very good review of solid propellant ignition models and their suitability for the internal ballistics modelling of guns has been given by Ref. [8].

QinetiQ has developed and used for many years a two-dimensional (2D), inviscid, multi-phase flow internal ballistics code named QIMIBS. QIMIBS uses equations typical of many computational fluid dynamic codes with combustion. It solves equations expressing the conservation of mass, momentum and energy in two dimensions using Riemann solvers. Solid phases are represented as a fluid. A key part of the development of QIMIBS has been to implement ignition submodels describing convective and radiative heating processes. However, it has been shown in experiments that non-gaseous combustion products from the igniter play a significant role in the ignition process [9]. Also, many pyrotechnics use energetic materials in the ignition train that produce mostly non-gaseous combustion products. Therefore, to improve the ignition modelling capabilities of QIMIBS for guns and to allow it to be used to model the ignition of rockets and pyrotechnics, submodels for heating due to conductive and condensative processes were developed and implemented.

QIMIBS models the heat input at the surface of the propellant grain and predicts the flow of heat within the grain using a standard one-dimensional heat conduction model. Ignition at the propellant surface is assumed to occur when the surface temperature exceeds a value specified by the user. This temperature is usually based on that measured in differential scanning calorimetry (DSC) tests, for example.

### 2.1. Convective heating model

This model is similar to that described and used in the United States Army Research Laboratory NOVA code [7].

The convective heat transferred to the solid propellant is given by Eq. (1)

$$q_c = h_v(T_g - T_s) \tag{1}$$

where $q_c$ is the convective heat flux, $h_v$ is the convective heat transfer coefficient, $T_g$ is the gas temperature and $T_s$ is the surface temperature of the solid propellant. In some codes, the gas temperature is replaced by a temperature known as the film temperature. The film temperature is the arithmetic average of the gas temperature and the propellant surface temperature. Use of a film temperature attempts to account for the possible presence of an insulating boundary layer near the propellant surface. However, no physical justification has been found for using an average of the gas and propellant surface temperatures. The use of the film temperature rather than the gas temperature will be to decrease the heat flux to the solid propellant (identical heat flux at ambient conditions but decreasing logarithmically with temperature to be 24% lower at 2000K). QIMIBS does not use a film temperature.

The heat transfer coefficient is calculated using the Nusselt number, Nu (Eq. (2)). In Eq. (2), k is the thermal conductivity of the gas evaluated at the gas temperature and D is an effective diameter of the solid propellant. The Nusselt number is effectively a dimensionless temperature gradient in the gas.

$$h_v = h_{v\mathrm{mult}} Nuk/D \tag{2}$$

QIMIBS uses a convective heating multiplier, $h_{v\mathrm{mult}}$, in Eq. (2) to account for inaccuracies in the ignition model or uncertainties in the propellant properties (e.g. the thermal conductivity or ignition temperature) in order to obtain good agreement with measured data for a particular propellant and igniter system. The convective heating multiplier should normally be unity unless experimental evidence indicates it should be increased or decreased.

The Nusselt number is calculated using the correlation of Gelperin and Einstein [5], Eq. (3a), for granular propellant, or Eq. (3b) for stick propellant [2]. The coefficients are likely to vary with surface roughness.

$$Nu = 0.4Re^{2/3}Pr^{1/3} \tag{3a}$$

$$Nu = 0.026Re^{0.8}Pr^{1/3} \tag{3b}$$

where $Re$ is the Reynolds number and $Pr$ is the Prandtl number. Eq. (3a) assumes the propellant bed is fluidised. When a fluid passes through a packed bed, it has been found that at a critical velocity (dependent on many factors such as fluid properties, particle geometry, etc) the fluid begins to carry the particles so that they start moving apart – at this point the bed is in a fluidised state. For non-