COMPARISONS OF INTERNAL BALLISTICS SIMULATIONS OF 40MM GUN FIRINGS

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Organisations from France, Germany and the UK are participating in a EUROPA Technical Arrangement (TA) research programme on Ignition Phenomena. The technical objectives of this programme are to study the ignition and combustion of conventional and novel solid propellants by conventional igniters, pyrotechnic igniters and plasma. A key part of the project is the development and incorporation of improved ignition and combustion submodels into internal ballistics codes in order to simulate ignition phenomena. Previous work compared simulations of a theoretical test case, known as the AGARD gun, which used granular propellant. The codes included one-dimensional (1D) and two-dimensional (2D) two-phase flow models. Further work has been conducted simulating 40mm gun firings that used a triple base propellant in slotted tubular geometry. This paper describes the 40mm gun firings, the codes, the propellant heating and ignition submodels and compares the predicted and measured results.

INTRODUCTION

ETBS, ISL and QinetiQ are participating in an European Undertakings for Research Organisation, Programmes and Activities (EUROPA) TA research programme on Ignition Phenomena. The technical objectives of this programme are to study the ignition and combustion of conventional and novel (low vulnerability ammunition (LOVA)/composite) solid propellants by conventional igniters (black powder), pyrotechnic igniters and plasma. A key part of the project is the development and incorporation of improved ignition and combustion submodels into internal ballistics codes in order to simulate ignition phenomena.

As part of the process of baselining each internal ballistics code and establishing its capabilities at the start of the TA, each participant simulated a standard test case. The test case selected was extracted from [1] and is known as the AGARD (Advisory Group for Aerospace Research and Development) gun. The codes compared included AMI from EMI and ISL, MOBIDIC from SNPE (SNPE is the creator of the code, ETBS and

ISL are users), and CTA1 and FHIBS from QinetiQ. These are all either 1D or 2D two-phase flow models. This work was reported in [2].

Further work was conducted, and reported in this paper, to compare the codes and, in particular, to determine how well their predictions agreed with fired results. QinetiQ supplied pressure data measured in 40mm gun firings that used a triple base propellant in slotted tubular geometry. This test case was substantially different from the AGARD test case which used granular propellant. Other measured data supplied included travel, velocity and acceleration data recorded using an in-bore Doppler radar system.

This paper describes the 40mm gun firings, the codes, the propellant heating and ignition submodels and compares the predicted and measured results

40MM GUN FIRINGS

These were conducted in a gun having a chamber volume of 600cc and a projectile travel of 3.0m. The masses of the propellant and projectile were 440g and 790g respectively. Ignition was achieved by means of a small bayonet primer (Figure 1) containing 4.2g of G12 gunpowder. The gaseous output from this primer has not been characterised. There are two rows of holes. Each row has four holes at 90° intervals. The centres of the two rows of holes are at 10mm and 35mm from the breech face. All holes have a radius of 2.5mm. The internal length of the primer is 50mm. The internal radius is 5mm. The paper envelope is assumed to have a burst pressure of ~2MPa.

This gun system and propellant have been used for many gun firings and produce very consistent maximum pressures and muzzle velocities (420MPa and 1230m/s respectively). Figure 2 compares the pressure profiles for three representative gun firings and shows the degree of variability in the ignition delay. Zero time is when the firing pulse was applied. The action time of the primer is variable but, on average, there is a time delay of 5ms between the application of the firing pulse and the first appearance of gases in the primer. Table 1 summarises the fired results.

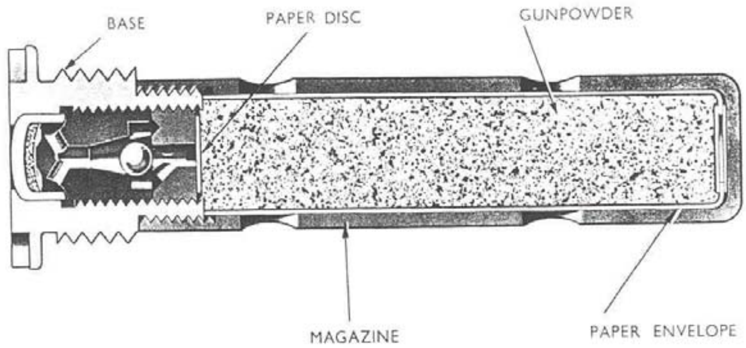

Figure 1. 40mm primer

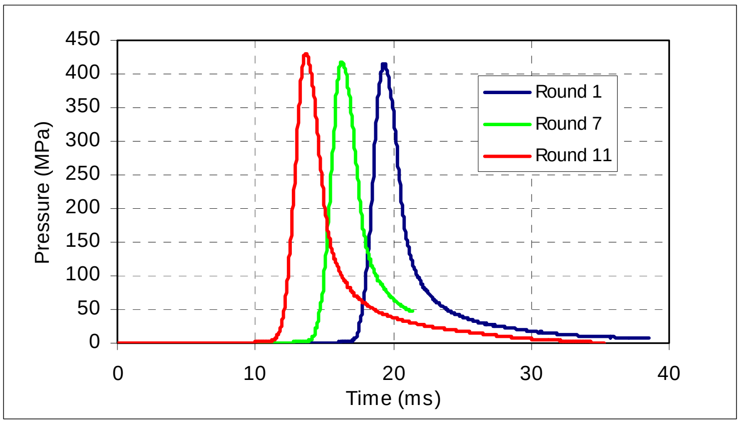

Figure 2. Comparisons of measured breech pressure profile

Table 1. Results of gun firings

Round	Propellant mass (g)	Projectile mass (g)	Maximum pressure (MPa)	Muzzle velocity (m/s)
1	437.95	789.05	420	1215
7	436.87	789.07	418	1229
11	437.77	789.94	428	1234

INPUT DATA

Table 2 lists the data supplied to each nation and used for the internal ballistics simulations.

Table 2. Details of the 40mm gun

Gun calibre (mm)	40
Chamber/gun profile:	
Distance from breech (mm):	0.000, 0.384, 0.434, 3.389
Diameter (mm):	42, 42, 40, 40 Chamber volume is 598cc
Initial position of projectile from breech face (mm)	434
Travel of projectile (mm)	2955
Distance from breech face to muzzle (mm)	3389
Engraving/bore resistance profile:	
Distance from breech (m)	0.434, 0.444, 0.445, 3.389
Resistive pressure (MPa)	14, 14, 8, 8 Note that this has not been measured but has been 'fitted'
Propellant solid density (g/cc)	1.63
Propellant geometry	Slotted tube
Propellant grain length (mm)	400
Propellant grain diameter (mm)	3.738
Propellant perforation diameter (mm)	0.945
Propellant burn rate coefficient (cm/s/MPa^n)	0.1118

Propellant burn rate pressure index (n)	0.9718
Propellant adiabatic flame temperature (K)	3416
Propellant ignition temperature (K)	444
Propellant thermal conductivity (W/s/K)	0.398
Propellant thermal diffusivity (mm^2/s)	0.169
Propellant emissivity (-)	0 (i.e. radiation is neglected)
Propellant chemical energy (MJ/kg)	5.071
Propellant molecular weight (g/mol)	24.32
Propellant specific heat ratio (-)	1.2303
Propellant impetus (MJ/kg)	1.1678
Propellant co-volume (cc/g)	1.018
Propellant intergranular wave speed (m/s)	Not used
Igniter mass (kg)	0.00415
Igniter density (g/cc)	1.7
Igniter geometry	Spherical
Igniter grain diameter (mm)	1.77
Igniter chemical energy (MJ/kg)	1.3045
Igniter molecular weight (g/mol)	57.94
Igniter specific heat ratio (-)	1.22
Igniter impetus (MJ/kg)	0.287
Igniter adiabatic flame temperature (K)	2000
Initial temperature of air & propellant in chamber (K)	294
Initial pressure	Atmospheric
Molecular weight of ambient air (g/mol)	29
Specific heat ratio of ambient air (-)	1.4

DESCRIPTION OF CODES

The internal ballistics codes used by the participants are shown in Table 3. Where available, references describing further details of each code are stated.

Table 3. Internal ballistics codes used

Name of code	Type (0D, 1D or 2D)	Propellant heating	Ignition criterion	User
CTA1 [3]	1D	No	Local gas temperature	QinetiQ
FHIBS [4]	2D	Yes	Propellant surface temperature	QinetiQ
AMI1D NG	1D	Yes	Propellant surface temperature	ISL
AMI2D	2D	Yes	Propellant surface temperature	ISL
MOBIDIC-NG [5]	2D	Yes	Propellant surface temperature	ISL, ETBS
SIBIL [6]	0D	No	Instant	ETBS

For simplicity, most internal ballistics models represent the igniter in the form of a tabular function of igniter flux versus time and location in the combustion chamber. This method has been used for some of the 1D and 2D simulations of the 40mm gun firings. In SIBIL, it was assumed that all of the igniter was burned at time zero. Explicit modelling of the igniter was also used for 1D simulations using the CTA1 code and 2D simulations using FHIBS.

Energy transfer from the igniter gas to the solid propellant is a contributory factor to the time interval between the igniter products first appearing and the propellant starting to burn. In the models shown in Table 3, the energy transfer is modelled in three different ways. The simplest model, as used in SIBIL, ignores the energy transfer process. Ignition of the propellant occurs instantaneously throughout the whole charge. CTA1 uses a slightly more realistic ignition model – ignition occurs when the local gas temperature exceeds a value specified by the user. This model does not simulate the energy transfer process from the igniter gas to the propellant. The other codes model the heating of the solid propellant by the igniter gas and use the surface temperature of the propellant as the ignition criterion. The heat transfer equations used in these models are very similar to those used in [7] and involve the use of heat transfer correlations to calculate the convective heating of the propellant grains.

COMPARISON OF PREDICTED RESULTS

Table 4 compares the predicted maximum pressures, muzzle velocities and time of shot exit data. The results show differences in the predicted maximum pressures and muzzle velocities. Some of these differences can be attributed to dissimilar submodels, such as those used for interphase drag, and to differences in the way the igniter was modelled.

Table 4. Comparison of predicted results

Code (ignition criterion)	Max breech pressure (MPa)	Max shot base pressure (MPa)	Muzzle velocity (m/s)	Shot exit time (ms)
Fired (mean)	428	-	1234	-
QinetiQ				
CTA1 - standard burn rate	463	357	1244	6.30
CTA1 - beta=0.107	426	329	1221	6.50
CTA1 - igniter as propellant	420	324	1221	9.26
FHIBS (gas temperature)	443	328	1246	8.13
FHIBS (granular heating)	441	329	1246	9.70
FHIBS (tubular heating)	440	329	1246	12.97
ISL/ETBS				
SIBIL – standard burn rate	561	439	1340	4.39
SIBIL - lower vivacity & impetus	418	327	1229	4.91
MOBIDIC-NG (tubular heating)	430	382	1295	6.66
MOBIDIC-NG (granular heating)	439	371	1283	6.09
AMI1D NG (perfect ignition, beta=0.102)	397	313	1273	5.87
AMI1D NG (heating, beta=0.102)	365	293	1249	6.62
AMI2D NG – reduced beta & impetus (heating)	407	334	1280	6.75
Beta is the burn rate coefficient and was reduced to match the measured results Perfect ignition assumes no grain heating – ignition occurs everywhere immediately				

Figures 3 and 4 compare the early time histories of the breech pressures for the 1D and 2D simulations respectively. The profiles have been aligned so that the instants of peak pressure are coincident.

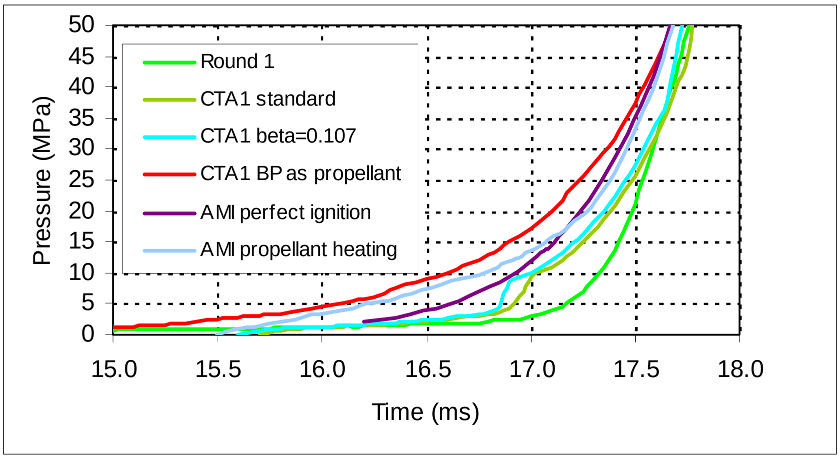

Figure 3. Comparisons of predicted breech pressures for 1D simulations

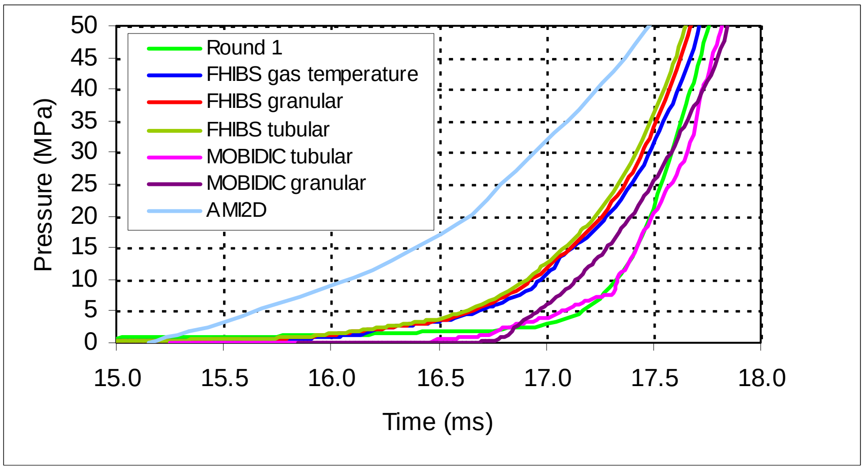

Figure 4. Comparisons of predicted breech pressures for 2D simulations

Figure 3 shows relatively sharp increases in predicted pressure for the two simulations of the CTA1 code in which the igniter was represented in the form of a table. The table defined a constant flux for 5ms over the region 0-5cm from the breech face. These sharp increases are caused by a pressure wave. This pressure wave is formed by the igniter discharge taking place over a small region of the combustion chamber, i.e. within 5cm of the breech face. The pressure wave propagates towards the projectile base, where it is reflected, and reaches the breech again after about 1.4ms (at 16.9ms in Figure 3). This pressure wave is much less evident in the other CTA1 simulation because the black powder was explicitly modelled as a propellant. In this case, the gas generation rate is much smaller, initially giving rise to a much smaller amplitude pressure wave. There is no sign of a pressure wave in the AMI perfect ignition case because it was assumed that all of the propellant was ignited simultaneously. Granular heating correlations were used for the AMI simulation with propellant heating. For both AMI simulations the igniter flux was represented in a tabular form. All simulations fail to match the sharp rise in the measured pressure profile in the region 17.0-17.5ms. This mismatch is probably due to the burn rate law being inaccurate at low pressures.

Figure 4 shows that the AMI2D profile rises at a slower rate than the other codes. The three FHIBS simulations, which all modelled the black powder as a separate burning propellant, are in good agreement. The two MOBIDIC simulations show best agreement with the measured pressure profile.

Figure 5 compares the 2D simulations with round 7, the round having an ignition delay closest to the mean ignition delay for the three rounds. The predicted pressure profiles have been adjusted by 5ms to allow for the delay in the primer action time. The order of the profiles is given by the legend, reading from left to right and then down. Clearly the MOBIDIC and AMI simulations predict shorter ignition delays than FHIBS. This is partly due to the representation of the igniter – in the MOBIDIC simulations it is represented as a table of constant flux for 5ms. Interestingly, whereas FHIBS shows a big difference in the ignition delay when using the granular and tubular heating correlations, MOBIDIC does not. The difference in ignition delay is not likely to be due to any differences in the heating correlations, which are similar for both codes. It is probably due to the fact that for FHIBS the igniter was simulated explicitly whereas for MOBIDIC it was introduced as a table of constant flux. This matter is being investigated further.

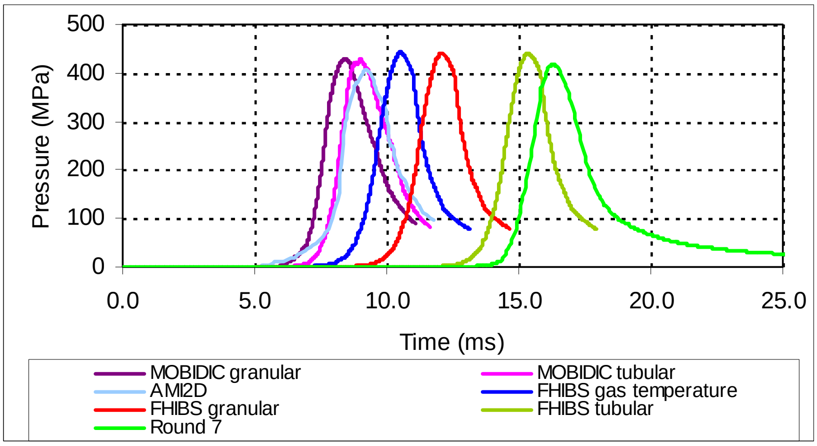

Figure 5. Comparison of ignition times for 2D simulations

Figure 6 compares the predicted pressure profiles using FHIBS with all three measured pressure profiles. Again the predicted pressures have been adjusted by 5ms to allow for the primer action time. The order of the profiles is given by the legend, reading from left to right and then down. Clearly the FHIBS simulation using the tubular heating correlation falls within the scatter of the measured pressure profiles.

CONCLUSIONS AND FURTHER WORK

Data from a good series of firings of a 40mm gun using propellant in slotted tubular geometry have been distributed to the EUROPA partners and made available to the internal ballistics community by publication of this paper. This will facilitate the understanding, development and comparisons of internal ballistics codes.

The 40mm gun firings have been modelled using a number of internal ballistics codes in wide use in France, Germany and the UK. The predicted results show some variations in the maximum breech pressures and muzzle velocities. These differences have been attributed to different submodels for interphase drag and methods of modelling the igniter.

Close comparisons of the predicted and measured pressures during the ignition phase showed differences caused by inadequacies of the burn rate data at low pressures. If the early measured pressure rise is to be predicted then it will be vital to determine accurate burn rate data at low pressures.

The results indicate that it may be possible to predict ignition delays of up to about 10ms by using an appropriate convective heating correlation function.

The next phase of this work will be to compare the predictions for a wider range of closed/vented vessel and gun firings.

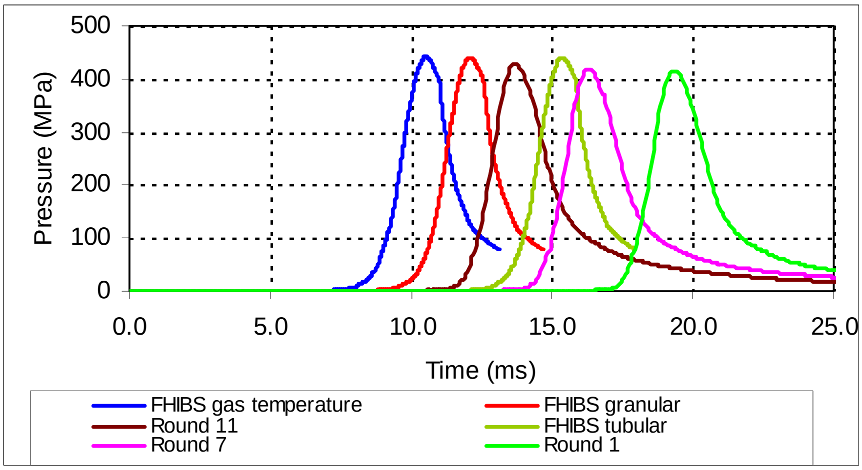

Figure 6. Comparison of ignition times for FHIBS simulations

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