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COMPARISON OF 0D AND 1D INTERIOR BALLISTIC MODELLING OF HIGH PERFORMANCE DIRECT FIRE GUNS

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The Defence Evaluation and Research Agency (DERA) is conducting research into electrothermal-chemical (ETC) tank guns. Part of this research is investigating the potential performance (muzzle velocity) of advanced charge concepts which are ignited by the application of ETC technology. Various interior ballistics models, including zero-dimensional (0D) and one-dimensional (1D) codes, are available to predict the muzzle velocity. However, there is some concern on the accuracy of 0D codes when used to predict the interior ballistics of high velocity guns. Therefore a study has been conducted comparing the predictions of 0D and 1D interior ballistic codes for high velocity ETC guns. The study investigated several advanced charge concepts that utilise high loading density propellant geometries. This paper describes the results from the comparative study that was conducted.

INTRODUCTION

Advanced charge concepts rely on high propellant progressivity (i.e. the gas generation rate increases through the use of either high burn rate propellants or propellant geometries that produce an increasing burning surface area as the propellant grain burns). High propellant progressivity means that most of the gas is generated during the late phase of the interior ballistics cycle, i.e. when the projectile is travelling at high velocity at some distance from the breech. A 0D code does not allow for gas dynamic effects in the sense that in a 0D code events taking place at the breech immediately affect also the conditions at the shot base. There is no allowance in a 0D code for the fact that events propagate at a speed that is dependent on the local speed of sound and that, as a consequence, there is a time delay before events occurring at the breech can affect the conditions at the projectile. As the velocity of the projectile increases then the time delay increases. A 1D code allows for these gas dynamic effects and should be more accurate than a 0D code.

Interior ballistic studies for high velocity ETC guns [1] have used 0D models. The results from these studies have indicated that substantial increases in muzzle kinetic energy (>40%) are theoretically possible through the use of high loading density charges, longer

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projectile travel, increased propellant impetus and moderation of the temperature coefficient. It is not known in the UK whether 0D models predict accurately the muzzle velocity of these gun systems. Therefore a study has been conducted comparing the predictions of 0D and 1D interior ballistic codes for high velocity ETC guns. The 0D code used was IBHVGETC [2] which was developed by the Army Research Laboratory. The 1D code used was CTA1 [3] which was developed by DERA.

APPROACH

Simulations were compared for three different propellant geometries: 19-perforated cylinders, full chamber diameter multi-perforated discs and full chamber diameter layered discs. The layered discs used 1:1 (effectively no faster burning layer) and 2:1 burn rate coefficient ratios (the inner layer had the larger burn rate coefficient). The propellant impetus used for the study was 1.3 MJ/kg which is representative of a very high energy propellant.

The results for two gun options were investigated in order to determine whether there were any trends going from current tank gun performance levels to near-future tank gun performance levels. Table 1 summarises the tank gun parameters. Some data have been normalised in order to aid comparisons. The barrel length was the same for both gun options. Identical electrical ignition pulses were used for the 0D and 1D simulations.

TABLE 1

Parameter	Gun 1	Gun 2
Calibre (mm)	120	120
Chamber volume (-)	1	+13%
Maximum chamber pressure (-)	1	+20%
Shot travel (-)	1	-3%
Shot mass (kg)	8	8

Identical input data were used for both the 0D and the 1D simulations. The procedure used for each propellant geometry was to increase the propellant mass by increments of 0.5 kg and then to adjust the propellant web size in order to achieve the required maximum breech pressure. For the layered propellant (2:1 burn rate coefficient ratio), the transition to the inner layer occurred after the maximum breech pressure had been attained, thereby producing a pressure profile with two peaks of about the same maximum pressure.

RESULTS

Muzzle velocities

Fig. 1 and Fig. 2 show the predicted 0D and 1D muzzle velocities for Gun 1 and Gun 2 respectively. Note that the muzzle velocities are relative to an arbitrary reference velocity. One general noteworthy feature is that, for the same propellant mass, the 1D muzzle velocities are greater than the corresponding 0D muzzle velocities by about 50–60 m/s (except for the high propellant masses).

For both gun options, the peak 0D and 1D muzzle velocities for layered disc propellant (1:1 burn rate coefficient ratio) occur at similar propellant masses. The curves for most of the other propellant shapes, as the propellant mass is increased, either continue to increase or begin to level off at a maximum muzzle velocity. The levelling off at a maximum muzzle velocity occurs at about 200 m/s and 300 m/s for Gun 1 and Gun 2 respectively. Referring to Fig. 1 and Fig. 2, for the layered disc (2:1 burn rate coefficient ratio), 19-perf and multi-perforated propellants the predicted 1D muzzle velocities, in general, are equalled by the predicted 0D muzzle velocities if about 2 kg of extra propellant is used.

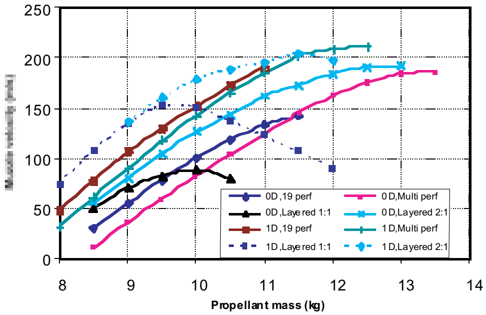

Figure 1.

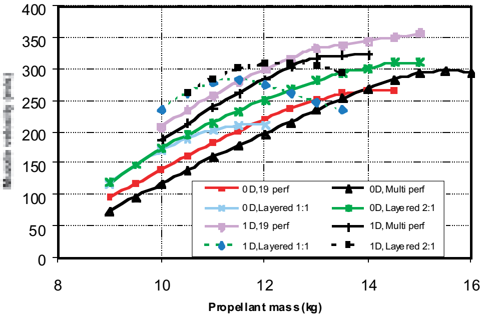

Figure 2.

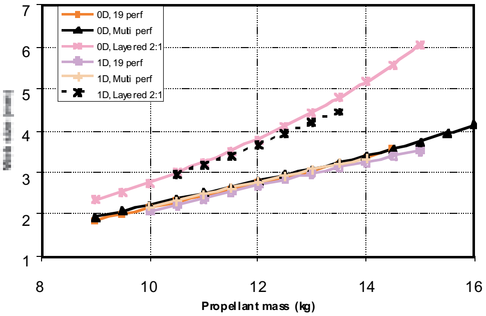

Figure 3.

Web sizes

Fig. 3 compares the web sizes required for Gun 2 (the graph for Gun 1 is similar). For each propellant shape, the web sizes required for the 0D and the 1D simulations are similar. However, there is a slight tendency for larger web sizes to be required for the 0D simulations. The curves for the layered disc propellant (1:1 burn rate coefficient ratio) are not shown because they are identical to those for the 2:1 burn rate coefficient ratio. Surprisingly there is little difference in the required web sizes for the 19-perforated cylindrical propellant grains and the multi-perforated propellant discs.

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Maximum shot base pressures

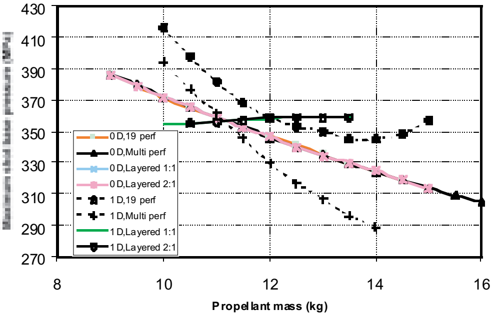

Figure 4.

Fig. 4 compares the predicted 0D and 1D maximum shot base pressures for Gun 2 (the curves for Gun 1 are similar but about 40–70 MPa lower). The curves for the layered disc propellant (1:1 burn rate coefficient ratio) are not shown because they are identical to those for the 2:1 burn rate coefficient ratio. When first seen, for the 0D results, it is remarkable how little the predicted maximum shot base pressures change with propellant geometry. Further thought reveals that the obvious cause for this is the Lagrangian approximation for the pressure gradient. This approximation is that the entire charge may at any time be assumed to be totally burned and that the density of the gas is constant along the gun barrel. This assumption leads to the well-known equations linking the breech pressure, mean pressure and shot base pressure, i.e. (neglecting resistive forces).

$$P_{mean} = P_{breech} - CP_{base} / 6W \quad \text{and} \quad P_{base} = P_{mean} / (1 + {}^{C}\!/_{3W}) \qquad (1)$$

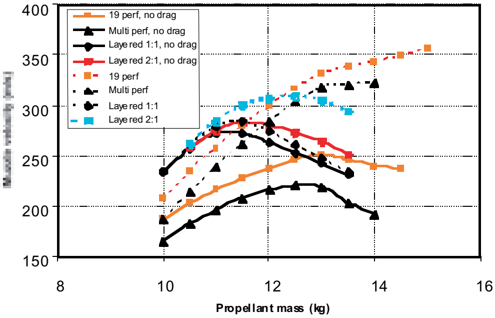

Figure 5.

where C is the propellant mass, W is the shot mass, P_{mean} is the mean pressure, P_{breech} is the breech pressure and P_{shot} is the shot base pressure. It is obvious that it is only the propellant mass and the shot mass that affect the pressure gradients in the 0D code; there is no direct dependence on the propellant geometry.

The 1D results show a much greater dependence of the maximum shot base pressures on the propellant geometry. It is interesting that there is little dependence of the maximum shot base pressure on the propellant mass for the layered disc propellant (1:1 and 2:1 burn rate ratios). An important finding from the 1D results is that, generally, use of the multiperforated propellant results in much lower maximum shot base pressures than any of the other propellant geometries considered.

DISCUSSION

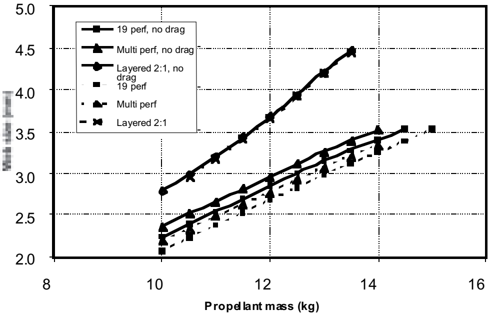

Figure 6.

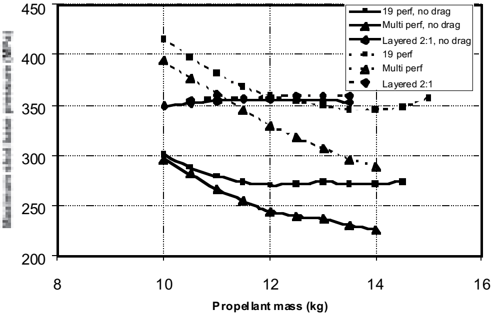

Figure 7.

One important difference between the 0D and 1D codes is in the calculation of the propellant burn rates. The 0D code assumes that the rate of burning everywhere in the barrel is dependent on the mean gas pressure, whereas the 1D code assumes that the rate of burning in a computational cell is dependent on the gas pressure in that cell. The crucial factor is the location of the propellant in the barrel during the internal ballistic cycle. If the propellant is near the breech during the combustion cycle then it will be burning at a pressure that is close to the breech pressure. If the propellant spreads out uniformly along the barrel then different parts of the propellant bed will be subjected to substantially different pressures and therefore will be burning at substantially different rates.

Intuitively it would be thought that the 1D simulations would be more accurate than the 0D simulations. However, if the interphase drag equations that are used in the 1D code are inaccurate then the 1D code may be predicting faster or slower movement of the unburned propellant than occurs in gun firings. The interphase drag equations [4] used in CTA1 are considered to be fairly accurate for small grains of propellant, i.e. 19-perforated cylindrical grains. There are no data on the accuracy of the interphase drag equations for full chamber diameter discs of propellant. The effect of interphase drag has been briefly studied in [5].

To determine the influence of the interphase drag on the 1D results, further simulations were conducted in which interphase drag was turned off. Zero interphase drag provides a limiting case. These simulations were conducted for Gun 2 only. Comparisons of the 1D results with and without drag are shown in Figs. 5–7.

Turning off interphase drag has the effect of reducing the muzzle velocities and reducing the charge mass at which an optimum muzzle velocity occurs. As expected, the web sizes required become larger and the maximum shot base pressures become lower for zero interphase drag. What is surprising is the invariance of the results for the layered disc propellants (1:1 and 2:1 burn rate coefficient ratios). There is very little change in the web sizes required or the predicted muzzle velocities or maximum shot base pressures.

Fig. 8 and Fig. 9 compare the predicted spatial profiles for the propellant bed porosity for normal drag and zero drag respectively, for different times in the internal ballistic cycle (layered disc propellant, 2:1 burn rate coefficient ratio). The conditions in the barrel are similar for the two simulations during the time period shown (3.0–4.8 ms). Maximum pressure occurs at about 4.9–5.0 ms. The two figures show a greater amount of propellant movement towards the shot base for the normal drag simulation than for the zero drag simulation. Note that propellant movement still occurs for the zero drag simulation because of the pressure gradient along the barrel.

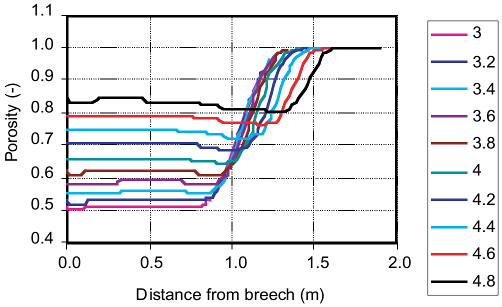

Figure 8.

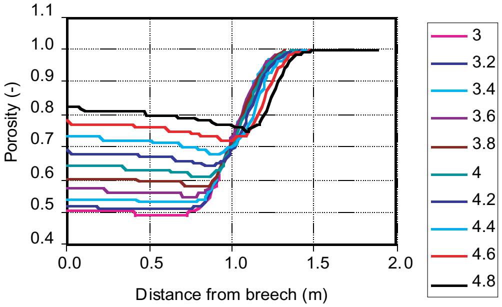

Figure 9.

Fig. 10 shows the predicted spatial profiles for the propellant bed porosity for normal drag for 19-perforated cylindrical propellant (the graph for zero drag is similar to Fig. 9). The conditions are similar to those for Fig. 8 and Fig. 9. Fig. 10 shows that there is much more propellant movement for the 19-perforated grains than there is for the layered disc propellant. This greater movement is the reason for the high 1D muzzle velocities and the high shot base pressures shown in Fig. 2 and Fig. 4 respectively. There is a ‘travelling charge’ effect.

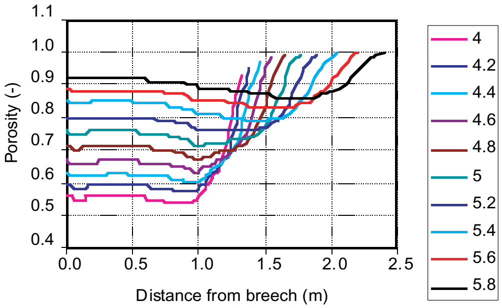

Figure 10.

Fig. 11 and Fig. 12 compare the predicted spatial profiles for the propellant bed porosity for normal drag and zero drag respectively for multiperforated propellant. The conditions are similar to those for Fig. 8 and Fig. 9. Fig. 12 shows similar porosity profiles to that shown in Fig. 9. Fig. 11 shows that there is much more propellant movement for the multiperforated grains than there is for the layered disc propellant, but less propellant movement than for the 19-perforated propellant grains. The comparative

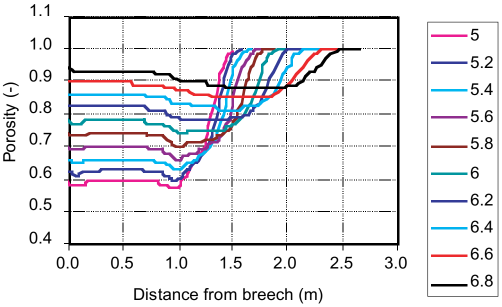

Figure 11.

lack of movement of the layered disc propellant is the reason for the similarity of the drag/no-drag results.

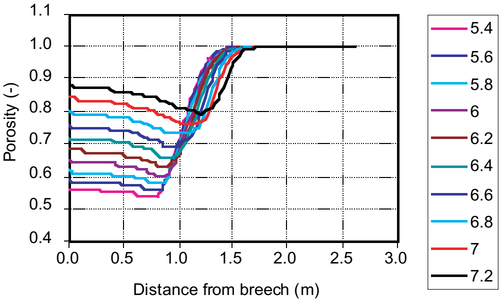

Figure 12.

Experiments should be conducted to ascertain the validity of the interphase drag equations for large diameter discs. Also, the validity of the 1D model for modelling full chamber diameter discs must be addressed. As is common to many 1D internal ballistics codes, the CTA1 code is a continuum model, modelling the solid propellant as a fluid rather than as individual tracked particles. An explicit assumption in deriving the mathematical model used in the CTA1 code is that the particle size is smaller than the size of a computational cell. Clearly for full diameter discs this assumption is violated. However, simulations, using CTA1, of gun firings using full chamber diameter discs has resulted in very good agreement between the predicted and measured projectile velocities and chamber pressures [6]. So although the assumption is violated of the particle size being small compared with the computational cell size, this violation does not appear to be critical to the calculations.

CONCLUSIONS AND FURTHER WORK

Comparisons between the predictions of 0D and 1D internal ballistics codes have shown significant differences in the muzzle velocities and maximum shot base pressures. The 1D code, CTA1, predicts higher muzzle velocities than the 0D code, IBHVGETC. One consequence of these differences is that the use of the 0D code, rather than a 1D code, will result in a conclusion that higher propellant masses (and hence loading densities) are required to attain a certain muzzle velocity.

The results of the 1D modelling are very dependent on the interphase drag between the gas and the solid propellant. Reducing the interphase drag results in lower muzzle velocities and lower maximum shot base pressures. Experiments should be conducted to ascertain the validity of the interphase drag equations for large diameter discs.

Results from the 0D code show that the calculated maximum shot base pressure is independent of the propellant grain geometry. This independence is due to the Lagrangian approximation for the pressure gradient. It is considered unlikely that the propellant grain geometry does not have some effect on the maximum shot base pressures.

An important finding from the 1D results is that, generally, use of the multiperforated propellant results in much lower maximum shot base pressures than any of the other propellant geometries considered.

Of the propellants considered, predictions for the layered propellant discs are least sensitive to the interphase drag.

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REFERENCES

1. W. F. Oberle & B. D. Goodell, 'The role of electrothermal-chemical (ETC) gun propulsion in enhancing direct-fire gun lethality', 16th International Symposium on Ballistics, San Francisco, September 1996.
2. J. Earnhart, N. Winsor & G. P. Wren, 'Electrothermal-chemical (ETC) extensions to IBHVG2 with a new user's tutorial', ARL-TR-348, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, January 1994.
3. C. R. Woodley, 'Development of a one-dimensional internal ballistics model of a cased telescoped ammunition gun', 15th International Symposium on Ballistics, Jerusalem, May 1995.
4. A. B. Crowley & A. D. Fitt, 'Accurate flame spread modelling for granular and stick propellants', 9th International Symposium on Ballistics, Shrivenham, UK, April 1986.
5. R. Heiser, 'Predictions of the performance of modern interior ballistics propulsion systems by standard codes', 18th International Symposium on Ballistics, San Antonio, November 1999.
6. C. R. Woodley, Unpublished DERA report, 1999.