19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

FLIGHT TEST RESULTS OF THE SWEDISH-DUTCH SOLID FUEL RAMJET PROPELLED PROJECTILE

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From 1995 to 2000 a co-operative study programme on Solid Fuel Ramjet propelled projectiles has been performed by FOI (formally FOA) and TNO-PML aiming at demonstration of this technology. Technology development work on aerodynamics, combustor and nozzle performance, projectile performance prediction, mechanical design and gun system enabled the design of a fin stabilized SFRJ projectile. Flight tests performed demonstrated that the projectile is capable of generating a thrust equal to its aerodynamic drag, resulting in a constant flight velocity capability. However, the flight tests also revealed problems with ignition and structural integrity of the fuel.

INTRODUCTION

The Solid Fuel Ramjet (SFRJ) propulsion system combines relatively high propulsion performance with a very low degree of mechanical complexity. As such, it is a very attractive propulsion system for gun launched projectiles. The functioning of a SFRJ projectile is, however, dictated by complex physical phenomena with strong interactions. A successful design of such a projectile thus requires detailed knowledge of the performance as well at subsystem level as at projectile system level.

Between July 1995 and December 1999 a co-operative study programme on SFRJ propulsion for projectiles was performed by the FOA Defence Research Establishment (nowadays called FOI), Weapons and Protection Division, in Sweden and the Prins Maurits Laboratory of the Netherlands Organisation for Applied Scientific Research (TNO-PML). The co-operation programme was extended to prepare and perform an additional flight test series in 2000. This study programme was financed by the Ammunition Branch of the National Supply Agency of the Royal Netherlands Army and the Swedish Defence Headquarters and Swedish Material Administration. The study programme aimed at demonstrating the technology of SFRJ propulsion for gun-launched projectiles by means of designing, manufacturing and flight testing a generic SFRJ propelled projectile.

TECHNOLOGY DEVELOPMENT

To direct the technology development effort, a so-called baseline design of the SFRJ projectile was defined early in the study programme based on requirements for typical anticipated applications (see Figure 1). Using this baseline design as a guideline a large number of activities have been performed during the past 5 years of the Swedish-Dutch SFRJ projectile programme on the following areas:

Figure 1. Baseline projectile design.

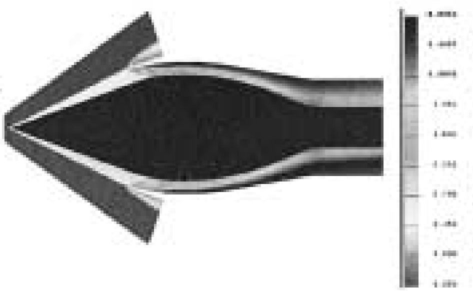

Figure 2. Mach number distribution in the air intake at 2 degrees angle of attack.

Aerodynamics

- prediction of projectile external drag components
- prediction of projectile stability characteristics
- detailed air intake performance calculations using Computational Fluid Dynamics (CFD) tools (see Figure 2)
- aerodynamic heating analysis of the most critical projectile components

Combustor and nozzle performance

- development of several fuels from which one fuel with sufficient mechanical and combustion performance has been selected
- mechanical tests of the fuel to verify the mechanical properties
- acceleration tests to verify structural integrity and bonding of the fuel
- nozzle performance calculations and nozzle performance sensitivity analysis
- improvement of the TNO-PML SFRJ test facility to better simulate the in-flight combustor entrance conditions
- combustor performance tests using the improved SFRJ test facility (see Fig. 3 and 5)
- CFD calculations and experiments using the SFRJ test facility which was further modified to investigate the in-flight ignition behaviour of the SFRJ combustor

Projectile system performance

- definition and subsequent updates of the projectile baseline design
- extensive improvement and validation of the Ramjet Propelled Projectile Performance Prediction Program RP^5 (see next chapter)
- baseline projectile performance prediction and projectile performance sensitivity calculations using RP^5 to direct the activities in all other technology areas and to enable design trade-offs

Mechanical design

- establishing a mechanical design including pusher plate and sabot segments
- acceleration tests of the projectile components and sub-assemblies to verify structural integrity
- finite element calculations to support the mechanical design and the acceleration tests

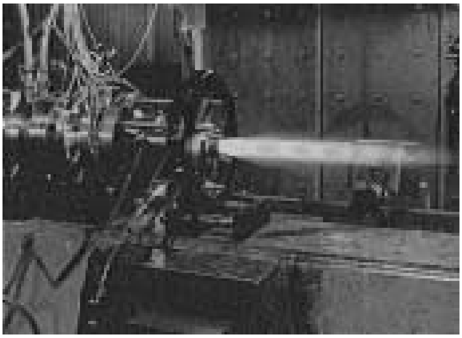

Figure 3. SFRJ combustor performance testing.

Figure 4. The gun system.

Gun system

- gun firings with dummy projectiles of different masses and using several different types and amounts of gun propellant to characterise the gun (see Figure 4) and to select a suitable gun propellant

The technology development activities listed above have been described extensively in [1,2].

DESCRIPTION OF RP^5

The RP^5 code is developed by TNO-PML to predict the flight performance of SFRJ projectiles taking off-design conditions into account [3, 4]. By assuming the thrust, drag and projectile mass to be constant during a small time step of the flight, a quasi-stationary flight calculation is performed.

At each time step the thermodynamic conditions and the chemical equilibrium composition of the gas flowing through the projectile are calculated at several stations throughout the system, assuming the flow to be one-dimensional. Shock wave relations in combination with the Taylor-Maccoll supersonic cone flow relations are used to predict the total pressure recovery and captured mass flow of the axi-symmetric single cone intake. The amount of fuel that evaporates and subsequently combusts is modelled using an empirical relation derived from a large number of SFRJ experiments. The projectiles net thrust then follows from subtracting the momentum entering the intake from the momentum leaving the exhaust nozzle.

The external cowl drag is predicted using the second-order shock-expansion method. Empirical relations are included to predict the cowl lip drag, skin friction drag, base drag as well as the drag due to bluntness of the fin leading and trailing edges. Subsonic and/or supersonic spillage drag at off-design flight conditions is accounted for.

Recent improvements of RP^5

Throughout the co-operation programme the RP^5 code has been improved substantially. A number of minor modifications concern the geometry handling capability of the code driven by the subsequent improvements of the baseline design. The most important improvements of the code are described below.

To predict the performance of the nozzle subsystem and its sensitivity to design changes a number of calculations has been performed using the Solid Performance Program (SPP code) [5]. The nozzle performance module of this computer code predicts the deficiencies with respect to the ideal inviscid one-dimensional nozzle flow in chemical equilibrium. The flow divergence loss is derived from an inviscid nozzle flow field calculation using the method of characteristics. A one-dimensional finite-rate chemical kinetics module is included to account for losses caused by the nozzle exhaust gases not being in chemical equilibrium. Furthermore, a boundary layer module is applied to predict the losses due to viscosity. Based on the results of the sensitivity analysis, several semi-empirical relations were derived which relate the above nozzle deficiencies to the parameters of influence. These semi-empirical relations subsequently have been implemented in RP^5 to improve the accuracy of the predicted thrust of the projectile.

To take into account the adverse viscous effects on the intake performance, a multiple linear regression analysis was performed on the intake CFD calculation results as listed under Aerodynamics Technology Development work. This resulted in a relation describing the total pressure recovery of the intake as a function of the flight Mach number and the static back pressure which was subsequently implemented in RP^5.

From the combustor performance experiments with the improved SFRJ test set-up using the ultra-sonic fuel regression rate measurement technique [6] it appeared that the combustion efficiency varied considerably during the burn time. An example of the primary data measured during an experiment is shown in Figure 5. From this data the combustion efficiency as a function of burn time is calculated. To take this important effect into account an empirical time dependent combustor performance model was derived, describing the fuel regression rate and the combustion efficiency as a function of momentary fuel grain port diameter and the momentary mass flow, total temperature and pressure of the air entering the combustor. The resulting time dependent combustor performance model has been implemented in RP[5].

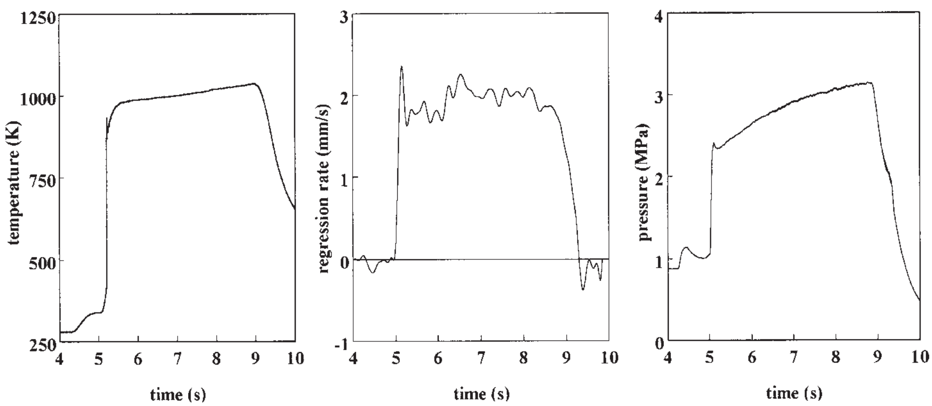

Figure 5. Total air temperature, fuel regression rate and combustion chamber pressure during burn-time.

FLIGHT TEST RESULTS

Prior to the flight test series with the final projectile design, several short range flight tests were performed with a simplified projectile intake configuration. These test firings have been described briefly in [1, 2] and more extensively in [7].

Three final test series were done at Bofors Test Centre in Sweden during the last quarter of 1999 and during the last quarter of 2000. In these tests the final design of the projectile was used with the air intake with a centre-body. The first of the final test series was performed in October 1999 on a 600 m test range. The aims of the first test series were to verify the mechanical design of the projectile as well as to verify the stability in flight with the final design of the air intake. Besides some gun warmers four projectiles were fired at zero degrees elevation. The muzzle velocity of these rounds as measured using a doppler radar varied between 1292 m/s (M=3.87) and 1332 m/s (M=3.98). The muzzle velocity was intentionally increased during the test series by increasing the amount of gun propellant. All projectiles showed quick and clean separation of pusher plate and sabots (see Figure 6) and a stable initial flight trajectory. However, none of the SFRJ projectiles showed evidence of ignition.

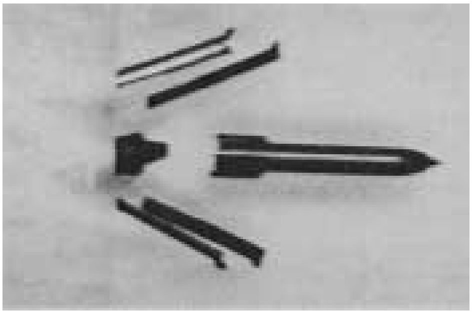

Figure 6. High-speed photo showing clean pusher plate and sabots separation.

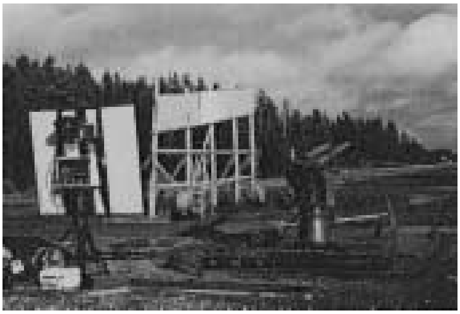

Figure 7. Impression of the test set-up of the flight test series.

The second test series was performed during the first week of December 1999 and aimed at achieving ignition and subsequently verify the flight performance of the SFRJ projectile on a test range more than 10 km long. Two different methods were applied to improve the ignition capability of the projectiles. During this test series a Weibel Doppler radar was used to track the projectile trajectory and to measure the velocity in flight and from that deduce the resulting force on the projectile (i.e. drag minus thrust). Figure 7 gives an impression of the test set-up. Ten projectiles (not counting gun warmers) were fired at 8 degrees elevation during two days. One projectile was fired without fuel for reference purposes. The muzzle velocity as measured using the Weibler Doppler radar varied between 1290 m/s (M=3.92) and 1382 m/s (M=4.14). The muzzle velocity was intentionally increased during the test series by elevating the temperature of the cartridge. All projectiles showed clean separation of pusher plate and sabots. For one projectile a highly unstable flight after separation of the pusher plate and sabots was observed. Four other projectiles showed a drag level significantly higher than that of the reference projectile. It is believed that such high drag levels can only occur when the flow of air through the projectile is (partially) blocked. Presumably, this blockage is caused by the solid fuel which apparently failed during gun launch.

Of the 10 projectiles fired, 4 showed a drag level lower than that of the reference round, indicating partial ignition. For one of these projectiles a transition occurred to full ignition, after which for a short time period a thrust was generated roughly equal to the drag. Figure 8 shows the resulting force coefficients of the latter round as well as the reference round as a function of the flight Mach number. Due to the partially ignited combustor, the initial resulting force of this SFRJ projectile is clearly lower than that of the reference projectile. But as soon as the combustor is fully ignited a thrust is generated which practically cancels the drag resulting in the flight velocity to remain essentially constant (see Figure 8).

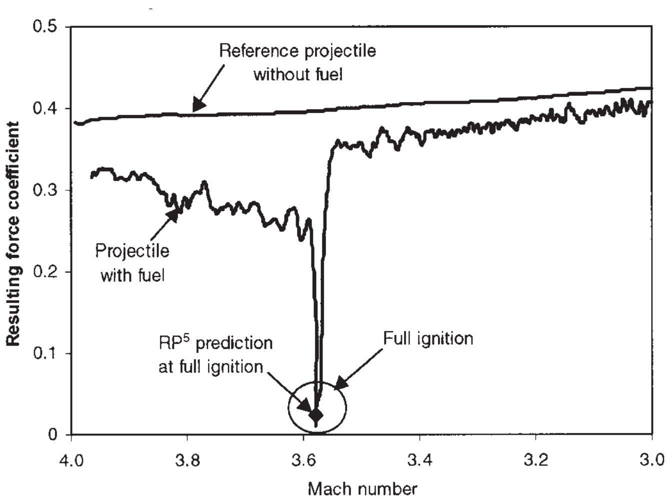

Figure 8. Comparison of measured and predicted resulting force coefficients.

The RP^5 computer code, as described in the provious chapter, has been used to predict the drag and the thrust of the projectile at the moment of full ignition. The resulting force coefficient as predicted by RP^5 is included in Figure 8. As can be seen, the performance level of the projectile is very well predicted by the computer code.

Based on the partial success of the second flight test series, it was proposed to perform a third free-flight test series with the aim to demonstrate a sustained propelled Mach 4 flight. Prior to the flight test series, acceleration tests demonstrated structural integrity of fuel grain samples up to acceleration levels beyond the anticipated flight test level. At the end of October 2000, 16 projectiles were fired using the same test set-up as during the second flight test series. Of these projectiles only 3 showed partial ignition, resulting in a resulting force somewhat lower tban the reference projectile without fuel. Most of the projectiles showed a drag level significantly higher than that of the reference round, again indicating problems with the structural integrity of the fuel.

Analysis of all data available indicates that the mechanical failure of the fuel may have been initiated by small local deformation of the projectile body. This deformation might be due to dynamic effects of the total projectile assembly during launch which inherently have not been accounted for during the acceleration tests on subsystem level.

CONCLUSIONS

From the work carried out within the framework of the Swedish-Dutch co-operation programme the following may be concluded:

1. On technology areas like, aerodynamics, combustor and nozzle performance, projectile performance prediction and mechanical design, the level of knowledge reached enables detailed design of a SFRJ projectile.
2. A design of a SFRJ propelled projectile has been conceived of which the mechanical functioning including clean separation of the pusher plate and sabot segments has been verified in actual gun firings.
3. The free-flight tests revealed serious ignition problems. In addition, the flight test data indicates structural integrity problems of the fuel.
4. The methods applied to improve the ignition capability have resulted in full ignition.
5. It has been demonstrated during free-flight tests that the SFRJ propulsion system is capable of generating a thrust which cancels the drag of the projectile resulting in an essentially constant flight velocity.

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