One-Dimensional Multiphase Flow Simulation of Internal Ballistics

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***Abstract*—This paper presents the development of a one-dimensional numerical model for simulating the internal ballistics of a high-caliber gun system. The model captures the coupled physical and chemical processes, including combustion, pressure evolution, heat transfer, and projectile dynamics. A finite-volume approach based on the Rusanov scheme is employed to solve the two-phase hyperbolic conservation equations governing compressible gas dynamics. Relevant source terms accounting for propellant combustion, drag forces, heat transfer, and projectile motion are incorporated into the formulation. A dynamic mesh technique is implemented to accommodate domain extension due to projectile travel. The model is applied to simulate the internal ballistic behavior of a virtual AGARD 132mm gun system, and the results are validated against data in the literature. The proposed framework offers a computationally efficient tool for analyzing internal ballistics and is well-suited for parametric studies, gun system optimization, and preliminary design evaluations. *Index Terms*—Internal ballistics, Simulation, One-dimensional model.**

I. Introduction

Internal ballistics refers to the study of the physical and chemical phenomena that occur within a gun propulsion system from the moment of ignition until the projectile exits the barrel. This includes ignition and combustion of the propellant, interaction between the generated gases and the unburnt charge, rapid pressure evolution, and the translational motion of the projectile through the barrel. Figure 1 presents a schematic representation of a high-caliber gun system. The modeling of internal ballistics presents significant challenges due to the highly transient nature of the process and the steep gradients in pressure and temperature. In addition, complex interactions such as the drag force between the unburnt charge and gases, heat transfer between gases and solid boundaries, and the coupled dynamics between the gas and projectile further complicate the simulation. Nevertheless, accurate internal ballistics modeling is essential for optimizing gun performance, enhancing projectile velocity, and ensuring the structural integrity of the system during firing.

Several one-dimensional models, such as that developed by Monreal-Gonzlez et al. [1], have demonstrated the ability to accurately predict pressure evolution and muzzle velocity in internal ballistic simulations while maintaining a balance between computational efficiency and physical fidelity. Multidimensional modeling of two-phase flows in interior ballistics, as explored by Nussbaum et al. [2], emphasizes the importance of capturing detailed gassolid interactions and pressure wave propagation. Despite this, many practical simulations continue to rely on one-dimensional formulations because of their reduced computational cost. Miura et al. [3] demonstrated the effectiveness of two-dimensional axisymmetric simulations in capturing the influence of propellant grain geometry on pressure development and projectile acceleration, underscoring the role of grain design in performance optimization. More recently, Krainov et al. [4] presented a comprehensive numerical model for nonstationary burning of solid propellants in controllable propulsion systems, highlighting the critical impact of pressure history on combustion behavior and reinforcing the need for coupled gassolid transient modeling. This work presents a

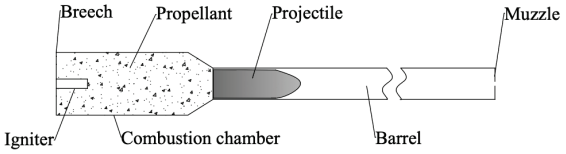

Fig. 1: Schematic diagram of a high caliber gun

one-dimensional computational model of a high-caliber gun system. To simplify the domain, the combustion chamber is assumed to be cylindrical, and the barrel is modeled as a tube of the same diameter. The propellant grains are initially placed inside the chamber, with an igniter located at the breech end. Upon ignition, the igniter releases hot gases that raise the temperature of nearby propellant grains above their self-ignition temperature. These propellants begin to combust, leading to a localized increase in temperature and pressure. The resulting hot gases propagate through the domain, heating the surfaces of the remaining propellant grains and initiating their ignition. When the pressure at the

projectile base exceeds the shot-start threshold, the projectile begins to move, traveling along the barrel, and eventually exiting through the muzzle. As the projectile advances, the available volume for combustion increases, which, after an initial rapid increase in chamber pressure, results in a subsequent drop in pressure.

II. Governing equations

This section outlines the governing equations used to model the internal ballistics of the gun system. The formulation is based on a one-dimensional representation, assuming flow along the axial direction of the barrel. The model includes conservation of mass and momentum for the gas and solid phases, conservation of energy for the solid phase, and an additional equation governing the evolution of the burnt propellant thickness. These equations collectively describe the complex coupled dynamics of combustion, gassolid interaction, and projectile motion during the firing cycle. The general form of the governing equations is given as follows:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}(\mathbf{U})}{\partial x} = \mathbf{S}(\mathbf{U}) \tag{1}$$

where conserved variable vector,

$$\mathbf{U} = \begin{pmatrix} \alpha_2\rho_2 \\ \alpha_1\rho_1 \\ \alpha_1\rho_1 u_1 \\ \alpha_2\rho_2 u_2 \\ \alpha_1 E_1 \\ d \end{pmatrix} \tag{2}$$

flux vector,

$$\mathbf{F}(\mathbf{U}) = \begin{pmatrix} \alpha_2\rho_2 u_2 \\ \alpha_1\rho_1 u_1 \\ \alpha_1(\rho_1 u_1^2 + P_1) \\ \alpha_2(\rho_2 u_2^2 + P_2) \\ \alpha_1 u_1(E_1 + P_1) \\ 0 \end{pmatrix} \tag{3}$$

and source vector,

$$\mathbf{S}(\mathbf{U}) = \begin{pmatrix} -\Gamma_c \\ \Gamma_c + \Gamma_{\text{ign}} \\ P_1 \frac{\partial \alpha_1}{\partial x} + \Gamma_c u_2 - F_D + \Gamma_{\text{ign}} u_{\text{ign}} \\ -P_1 \frac{\partial \alpha_1}{\partial x} - \Gamma_c u_2 + F_D \\ -P_1 \frac{\partial (\alpha_2 u_2)}{\partial x} + \Gamma_c \left(Q_{\text{ex}} + \frac{P_1}{\rho_2} + \frac{u_2^2}{2} \right) - u_2 F_D - A_s q_t + \Gamma_{\text{ign}} Q_{\text{ign}} \\ \dot{r} - u_2 \frac{\partial d}{\partial x} \end{pmatrix} \tag{4}$$

Here, α_k denotes the volume fraction, ρ_i is the density, u_i is the velocity, P_i is the pressure, E_i is the total energy of phase i. The index $i = 1$ corresponds to the gas phase, while $i = 2$ represents the solid phase. The gas phase is treated as compressible, whereas the solid phase is considered incompressible. The thickness of the burnt layer is indicated by d.

In the source terms of the governing equations, Γ_c denotes the mass transfer rate due to propellant combustion, while Γ_{ign} represents the mass transfer rate from the igniter. F_D is the interfacial drag force between the gas and solid phases. Q_{ex} refers to the energy released during the combustion of the propellant, and Q_{ign} is the energy released by the igniter. A_s denoted the specific surface area of the propellant available for combustion, and q_t represents the heat flux from gas phase to the surface of the propellant grain.

A. Closure relationships

The physical interaction between gas and solid phases, as well as the thermodynamic behavior of the system, is described through appropriate closure relations. These relationships are essential to complete the system of governing equations and accurately capture the coupling between the phases. Given the high pressures and temperatures that develop during the internal ballistic cycle, the NobleAbel equation of state is employed to model the thermodynamic properties of the gas phase. This equation accounts for the finite volume occupied by gas molecules, making it more suitable than the ideal gas law under the extreme conditions present inside the combustion chamber.

$$P_1 = \frac{(\gamma - 1)\rho_1 e_1}{1 - \eta\rho_1} \tag{5}$$

where γ is the ratio of specific heats, e_1 is the specific internal energy, and η is the covolume. The total specific energy of the gas phase is defined as:

$$E_1 = \rho_1 \left(e_1 + \frac{u_1^2}{2} \right) \tag{6}$$

The pressure in the solid phase is modeled by accounting for an intragranular stress term, R_p and is given by:

$$P_2 = P_1 + R_p \tag{7}$$

The intragranular stress R_p is defined as: [5]

$$R_p = \begin{cases} 0, & \text{if } \alpha_1 > \alpha_c \\ \dfrac{\rho_2 c_p^2 \alpha_c (\alpha_c - \alpha_1)}{\alpha_1 (1 - \alpha_1)}, & \text{if } \alpha_1 \leq \alpha_c \end{cases} \tag{8}$$

Here, α_c is the critical porosity (assumed to be the initial porosity), and c_p is the speed of sound through the propellant inside the combustion chamber. The interfacial drag force D between the gas and the solid phase is modeled using the correlation developed by Ergun [6], and is given by:

$$D = f_r \cdot \frac{\phi(\alpha_2)}{6} \cdot \rho_2 (1 - \alpha_2) \cdot \frac{S_p}{V_p} \cdot (u_1 - u_2) \, |u_1 - u_2| \tag{9}$$

Here f_r is the resistive factor. The function ϕ depends on the shape of the grain.

$$\phi(\alpha_2) = \begin{cases} 0.3, & \text{if } \alpha_2 > 0.9 \\ 1.75 \left(\dfrac{1 - \alpha_2}{\alpha_2} \cdot \dfrac{\alpha_c}{1 - \alpha_c} \right)^{0.45}, & \text{if } \alpha_c < \alpha_2 \leq 0.9 \\ 1.75, & \text{if } \alpha_2 \leq \alpha_c \end{cases} \tag{10}$$

The rate of propellant combustion is estimated using Vieille's law [7], which relates the linear burning rate to the local gas pressure:

$$\dot{r} = a P_1^n \tag{11}$$

where $\dot{r}$ is the burning rate, a and n are empirical constants. The mass transfer rate due to propellant combustion, Γ_c is then calculated as:

$$\Gamma_c = (1 - \alpha_1) \cdot \frac{S_p}{V_p} \cdot \rho_2 \cdot \dot{r} \tag{12}$$

Here, S_p and V_p are the instantaneous surface area and volume of a single propellant grain, respectively. It can be estimated as:

$$S_p = \pi(L_0 - 2d)\left[(D_0 - 2d) + 7(d_0 + 2d)\right] + \frac{\pi}{2}\left[(D_0 - 2d)^2 - 7(d_0 + 2d)^2\right] \quad (13)$$

$$V_p = \frac{\pi}{4}(L_0 - 2d)\left[(D_0 - 2d)^2 - 7(d_0 + 2d)^2\right] \quad (14)$$

where, L_0 is the initial length of the propellant, D_0 is the initial diameter and d_0 is the diameter of perforation. The heat flux from the gas phase to the solid propellant is estimated using Newtons law of cooling:

$$q_t = h_t(T_1 - T_2) \quad (15)$$

where h_t is the heat transfer coefficient, and T_1 and T_2 are the temperatures of the gas and propellant, respectively.

III. Numerical method

A finite volume method is employed for the numerical solution of the governing equations [8]. To improve stability and accuracy, a splitting technique is applied in which the convective and source terms are treated separately. This operator-splitting approach allows the solution of the hyperbolic and source-driven parts of the system in two distinct steps. The convective part of the governing equation is given by:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}(\mathbf{U})}{\partial x} = 0 \quad (16)$$

The source term is treated separately as an ordinary differential equation (ODE):

$$\frac{d\mathbf{U}}{dt} = \mathbf{S}(\mathbf{U}) \quad (17)$$

For the convective step, the spatial domain is discretized using a uniform grid and the conservative update at each cell i is given by:

$$\mathbf{U}_i^{n+1} = \mathbf{U}_i^n - \frac{\Delta t}{\Delta x}\left(\mathbf{F}_{i+1/2} - \mathbf{F}_{i-1/2}\right) \quad (18)$$

where $F_{i-1/2}$ is the numerical flux values at the interfaces which is solved by using Rusanov method.

IV. Results and Discussion

The one-dimensional computational fluid dynamics model developed in this work was applied to simulate the firing cycle of a virtual AGARD 132 mm gun system. All input parameters, including geometrical details, thermochemical properties, and propellant characteristics, were adopted from Reference [9] to ensure consistency with established benchmarks. Figure 2 illustrates the pressure evolution at the breech and shot base during the firing cycle. Initially, the pressure at both locations remains low until ignition occurs, followed by a rapid rise in pressure. Once the pressure at the shot base exceeds the shot-start threshold, the projectile begins to move, causing a dynamic increase in the combustion chamber volume. This expansion leads to a sharp drop in pressure after reaching the peak. The pressure at the breech remains consistently higher than at the shot base due to the proximity of the igniter and the direction of gas expansion. The peak pressure predicted by the model remains within the acceptable range for the AGARD 132 mm gun system, as summarized in Table 1.

TABLE I: Comparison of computed results with acceptable performance range for the AGARD 132 mm gun system.

Parameter	Acceptable Range	Computed Value
Maximal shot base pressure (MPa)	325–360	357.7
Maximal breech pressure (MPa)	355–400	389.126
Muzzle velocity (m/s)	660–705	698
Shot exit time (ms)	14.66–16.58	15.7

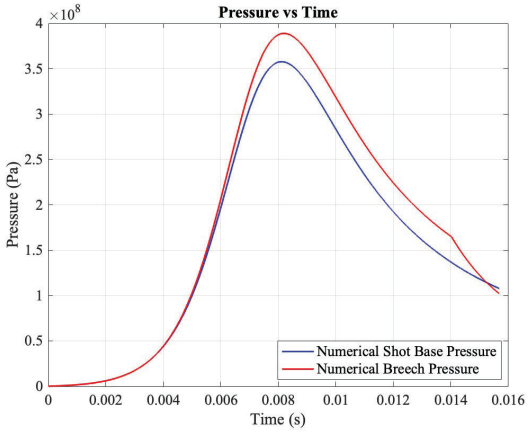

Fig. 2: Evolution of pressure at breech and at shot base

Figure 3 presents the time history of projectile velocity. For approximately the first 3.5 ms, the projectile remains stationary because the pressure at the shot base is below the shot start threshold. Once this threshold is exceeded, the projectile accelerates rapidly along the barrel under the action of the high pressure gases. The velocity rises steeply during the early phase owing to intense propellant combustion; thereafter, the rate of increase diminishes as the gases expand and chamber pressure falls. The velocity attained at the barrel exitreferred to as the muzzle velocityis a key performance metric for gun design. The model predicts a muzzle velocity of 698 m/s, which lies within the acceptable limits specified for the AGARD 132 mm gun system (Table 1). Figure 4

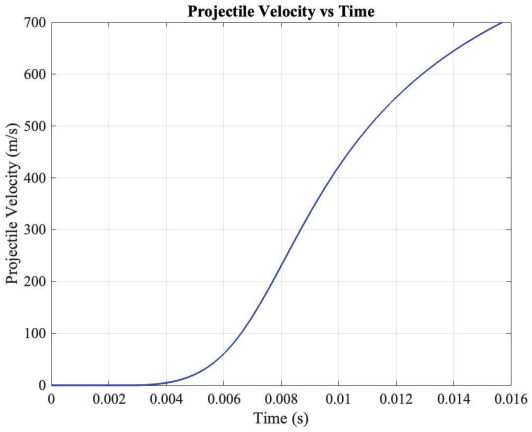

Fig. 3: Evolution of projectile velocity inside the gun

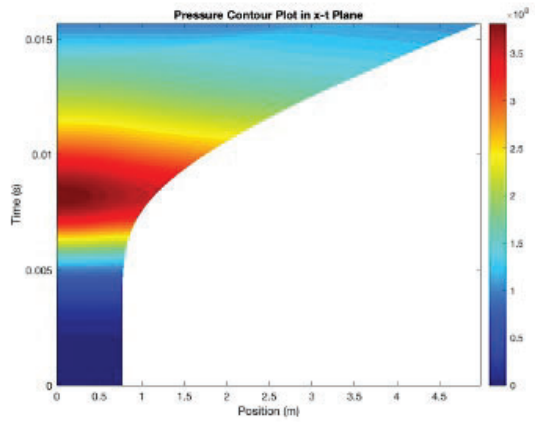

Fig. 4: Pressure contour diagram

shows the spatiotemporal distribution of pressure within the combustion chamber and barrel during the ballistic cycle. The x–t diagram illustrates the propagation of the pressure wave along the length of the gun system, from the breech toward the muzzle, as a function of time. The figure clearly captures the expansion of gases and the influence of projectile motion on the evolving pressure field. Key physical phenomenasuch as the development of pressure gradients and the transition from a confined combustion zone to an expanding one due to projectile movementare evident in this visualization. This figure highlights the highly transient and spatially non-uniform nature of internal ballistics, emphasizing the importance of time-accurate and spatially resolved modeling for accurate performance prediction.

V. **Conclusion**

A one-dimensional computational model was developed to simulate the internal ballistics of a high-caliber gun system. The model successfully captured the complex interactions between propellant combustion, gas dynamics, and projectile motion. It was applied to a virtual AGARD 132 mm gun system, predicting both the pressure evolution within the combustion chamber and the projectile motion. The computed peak pressure and muzzle velocity were found to be within acceptable ranges. These results highlight the models capability to represent the highly transient and nonlinear nature of internal ballistics, offering valuable insights for design optimization and performance evaluation of gun systems.

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