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INTERIOR BALLISTIC STUDY WITH DIFFERENT TOOLS

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ABSTRACT

Recently, the designers of gun and ammunition need different models to simulate the initial design concepts especially to make decision about optimum charge design and overall parameters of gun systems by using a mathematical optimization code coupled with the interior ballistic code. Nowadays, there are several available tools simulating the interior ballistic process; each tool has its advantages and its accessible outputs. In this work, interior ballistic lumped parameter model (IBLPM), with single propellant and mixed propellant, and one dimensional two-phase flow model (1D-TPFM) are carried out. Comparisons between obtained results for the different tools and experimental results are presented. This study is valuable to decide which interior ballistic tools will be appropriate to couple with the optimization codes for obtaining the optimum charge design.

Keywords: Interior ballistic, lumped parameter model, two phase flow model

1. INTRODUCTION

Due to the sequential evolutions in the ammunitions and gun systems, the modeling of gun interior ballistic process becomes very crucial. Computer simulations supply fast and cost-effective methods of prediction and evaluation of the interior ballistic performance according to geometry of guns and different propellant charges. Interior ballistic models can be used to address the problems and solutions for undesirable ballistic performance [1-3]; such as high pressure wave, gun blow and incomplete burning of the propelling charge.

Interior ballistic models are different in complexity. The selection of model is depended on the designer's requirements. For example, if the designer studies optimization of the propelling charge, the interior ballistic model should be simple and fast to save the computations time as it coupled with the optimization code.

The tools of the interior ballistics have been performed in sequence of the IBLPM, one dimensional two-phase flow model, and multi-dimensional two-phase model. The IBLPM has been used for the prediction of interior ballistics parameters [4], this model is simple and very useful to study the gun performance and to design the grain geometry. The computation time for this model takes almost few seconds. Hence, it will be very useful when propelling charge optimizations are required. IBLPM will not be suitable to use when the study on ignition inducing pressure waves is required.

he two-phase flow codes are very crucial when the study on ignition and flame spreading is required or analyzing the propelling charge position in the chamber. This model has been used depending on fluid mechanics approach [5], formulating the governing equations of the mass, momentum and energy for the both phases over a control volume of the gas and solid phases using the Eulerian-Eulerian approach. Quasi one dimensional two-phase flow model (XKTC) has been presented based on the conservation equation for a single solid particle and the fluid [6]. This approach has been extended to the multidimensional two-phase flow model (NGEN) [7]. The computations time for NGEN codes takes almost some days using the personal computers. Hence, it will not be appropriate when the optimization of propelling charge is required to study.

In this study, the IBLPM and the 1D-TPFM are developed for a naval medium caliber gun. The IBLPM is carried out utilizing two different types of propelling charge; single propelling charge, consisting of granular seven perforated propellant, coupled with igniter, and mixed propelling charge consists of granular seven perforated propellant and tubular propellant. 1D-TPFM is carried out utilizing single propellant coupled with igniter.

2. GENERIC PROBLEM TREATED AT ALL MODELS

To explicate the interior ballistic process with using different models, 76 mm naval medium caliber gun is selected; gun geometry is illustrated in Table1. Two types of propelling charge are used; the first type is used with IBLPM-single propellant and TPFM, the second type is used with IBLPM-mixed propellant.

The single propellant charge consists of 2.46 kg of granular 7-perforated propellant with density 1550 kg/m^3 coupled with igniter as shown in Fig. 1. While, the mixed propellant charge consists of 2.46 kg of granular 7-perforated propellant with density 1550 kg/m^3 and 0.2 kg tubular one hole propellant with density 1540 kg/m^3, as shown in Fig. 2.

Table 1. Data of 76 mm Naval Gun

Parameter	Value	Unit
Gun Caliber	0.076	m
Tube Length	4.045	m
Chamber Length	0.38	m
Projectile Mass	5.9	Kg
Chamber Volume	0.00354	m^3

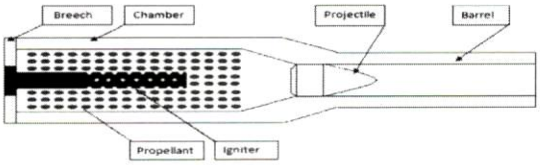

Fig.1. Gun system geometry with single propelling charge.

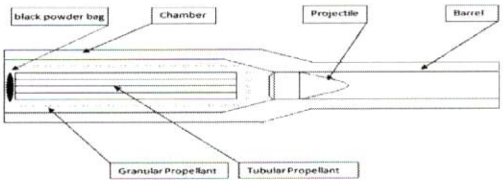

Fig.2. Gun system geometry with mixed propelling charge

3. IBLPM SIMULATION

The IBLPM is widely used for the prediction of interior ballistic parameters such as peak pressure and muzzle velocity. Moreover, this model is very simple and useful in the interior ballistic cycle; it is formed by a system of ordinary differential equations solved numerically together. In IBLPM it is assumed that the propelling charge is instantaneously and uniformly ignited [8-9]. It is not required to consider the position of the propelling charge. The general form of IBLPM is represented as follow in Eqn.(1):

$$\left.\begin{aligned}
&\psi_i = \chi_i Z_i (1 + \lambda_i Z_i + \mu_i Z_i^2) \\
&\frac{dZ_i}{dt} = \frac{u_{1i}}{e_{1i}} p^{ni} \qquad\qquad i = 1, 2, \ldots, n \\
&\frac{dv}{dt} = \frac{S.p}{\phi.m} \\
&\frac{dl}{dt} = v \\
&S.p(l_\psi + l) = \sum_{i=1}^{n} f_i \omega_i \psi_i - \frac{(k-1)\phi m}{2} v^2
\end{aligned}\right\} \qquad (1)$$

Where ψ_i is the relative burnt percentage of the i-th propellant, Z_i is the relative burnt thickness of the i-th propellant, χ_i, λ_i and μ_i are characteristic parameters of the i-th propellant, u_{1i} is the burning rate coefficient of the i-th propellant, e_{1i} is the half web thickness of the i-th propellant (m), p is the pressure in the chamber (Mpa), n_i is the burning rate pressure index of the i-th propellant, φ is the coefficient accounting for the secondary energy losses, m is the projectile mass (Kg), v is the projectile velocity (m/s), S is the barrel cross-section area (m^2), l is the tube length (m), l_ψ is the ratio of chamber free volume to the bore area, f is the impetus force of the i-th propellant (J/Kg), ω_i is mass of the i-th propellant (Kg), k is propellant specific heat ratio.

Each propelling charge type has its own advantages and disadvantages. For example, the granular propellant has a high charge density [10]. First thinking is that the granular propellant will be the most effective charge because it will increase the muzzle velocity of the projectile, but it is not true. As the charge density increases, the air permeability of the propellant bed decreases and the pressure behind the projectile increases which may result in unsafe firing. On the other hand, the tubular propellant has air permeability better than the granular propellant. Hence, the resistance of gas flow through the tubular propellant is less than through granular propellant. In addition, it reduces the pressure wave but it has small charge density which will not achieve the muzzle velocity of the projectile [8]. So, mixing of these two propellants will be very useful and effective to achieve their both advantages and the safety launch requirements. The mixture of granular propellant and tubular propellant will increase the permeability of the charge which decreases the pressure. Hence, the safety launch will be achieved, also the charge density will not be low and the burning will be progressive to increase the muzzle velocity.

In this section the interior ballistic process is simulated using two different tools; IBLPM-single propellant and IBLPM-mixed propellant. The required inputs data for these two different models are straightforward and simple such as; chamber volume, tube diameter, tube length, projectile mass, propelling charge mass, charge geometry and burning rates. The obtained data are represented as projectile muzzle velocity, peak pressure and muzzle pressure. This model is simple but very useful. the computation time takes almost few seconds. So, it will be very useful for studying the optimization of the propelling charge.

The obtained results of IBLPM-single propellant are 980.54 m/s muzzle velocity, 349.2 MPa peak pressure and 78.96 MPa muzzle pressure. While, the obtained results of IBLPM-mixed propellant are 983.27 m/s muzzle velocity, 344.3 MPa peak pressure and 87.79 MPa muzzle pressure. These data are illustrated in Figs. (3-4).

From the obtained results of the IBLPM, it is found that, the use of mixed propellant decreases the peak pressure and increases the muzzle velocity. But the muzzle pressure is increased. So, it is very important to use an optimization code coupled with the IBLPM code to find the optimum charge design that decrease the muzzle pressure and the peak pressure and increase the muzzle velocity.

4. 1D-TPFM SIMULATION

The importance of the two phase flow simulation appears when the study of ignition and flame spreading is required.

Moreover, study of pressure waves, propellant geometry, propellant location, loading density and combustion.

The required inputs data for 1D-TPFM is not only as those for IBLPM, but it needs some additional requirements such as axial boundaries of propellant charge, chamber geometry, ignition temperature and parameters describing propelling charge compressibility. Some of these additional requirements are often not available for the propelling charges [11]. The 1D-TPFM is appropriate. Even, it has such level of complexity. The computation time of this model takes almost 8-10 minutes using the personal computers.

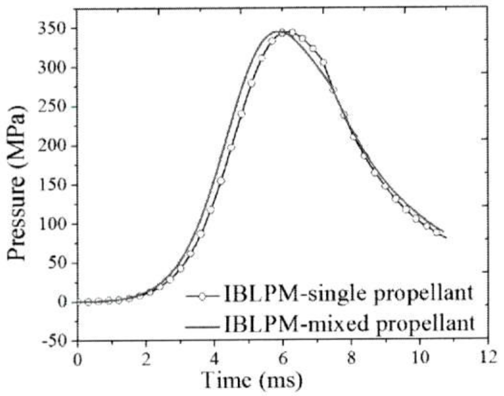

Fig.3. Pressure-vs-time curves for IBLPM

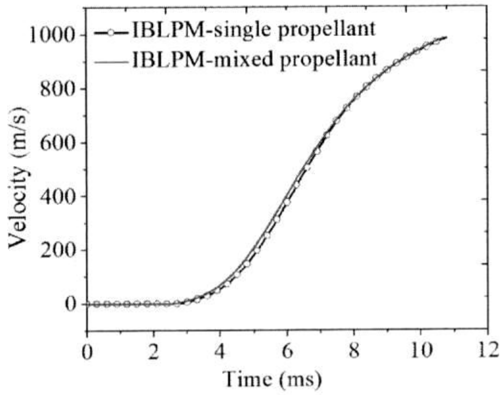

Fig.4. Projectile velocity curves for IBLPM

The governing equations of the 1D-TPFM are solved as a one-dimensional two-phase flow of nonlinear hyperbolic partial differential equations. These equations can be written as follows [12-13]:

$$\frac{\partial U}{\partial t}+\frac{\partial E}{\partial x}=S \tag{2}$$

Where, U, E, S are the conserved variables, the flux vector and the source vector respectively.

The components of U are the conserved variables:

$$U=\begin{pmatrix}U_1\\U_2\\U_3\\U_4\\U_5\end{pmatrix}=\begin{pmatrix}\varphi\rho_g A\\(1-\varphi)\rho_p A\\\varphi\rho_g u_g A\\(1-\varphi)\rho_p u_p A\\\varphi\rho_g(e_g+u_g^2/2)A\end{pmatrix} \tag{3}$$

The components of E are the flux functions:

$$E=\begin{pmatrix}E_1\\E_2\\E_3\\E_4\\E_5\end{pmatrix}=\begin{pmatrix}\varphi\rho_g u_g A\\(1-\varphi)\rho_p u_p A\\\varphi\rho_g u_g^2 A\\(1-\varphi)(\rho_p u_p^2+R_p)A\\\varphi\rho_g u_g(e_g+u_g^2/2+p/\rho_g)A\end{pmatrix} \tag{4}$$

And the components of S are the source term functions:

$$S=\begin{pmatrix}S_1\\S_2\\S_3\\S_4\\S_5\end{pmatrix}$$

$$=\begin{pmatrix}\dot{m}_c A+\sum\dot{m}_{ign}A+\dot{m}_k A\\-\dot{m}_c A\\-f_s A+\dot{m}_c u_p A+\sum\dot{m}_{ign}u_{ign}A+\dot{m}_k u_k A-(\varphi A)\nabla p\\f_s A-\dot{m}_c u_p A-(1-\varphi)A\nabla p\\\begin{pmatrix}-Q_p A-f_s u_p A+\dot{m}_c A(e_p+p/\rho_p+u_p\cdot u_p/2)\\+\sum\dot{m}_{ign}H_{ign}A+\dot{m}_k H_k A-p\dfrac{\partial(A\varphi)}{\partial t}\end{pmatrix}\end{pmatrix} \tag{5}$$

Where; φ is the volume fraction of the gas phase, u_g, u_p are the gas and solid velocity. ρ_g, ρ_p are the gas and the solid density. P, e_g are the pressure and internal energy of the gas phase. $\dot{m}_c$ is the rate of gas mass generation due to propellant combustion. $\dot{m}_{ign}$ is the mass flow rate of gas from vent holes of the igniter. H_{ign} is the stagnation enthalpy of the gas flow from vent holes. f_s, R_p and Q_p are interphase drag, intergranular stress, and interphase heat transfer respectively.

The obtained results of 1D-TPFM are 984.75 m/s muzzle velocity, 342.8 MPa peak pressure and 68.7 MPa muzzle pressure. These data are illustrated in Figs. (5-6).

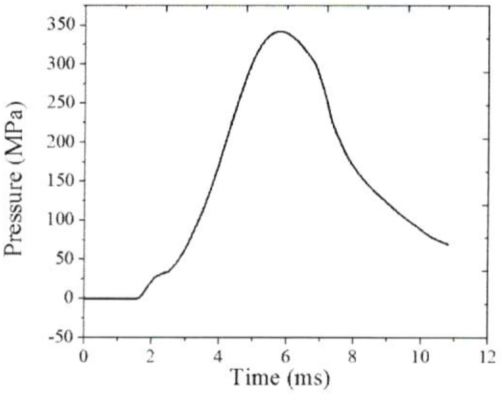

Fig.5. Pressure-vs-time curves for 1D-TPFM

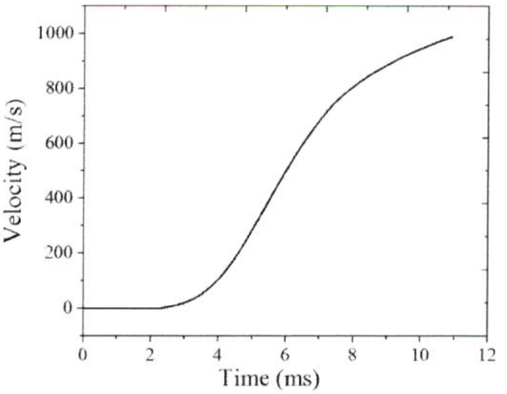

Fig.6. Projectile velocity curve for 1D-TPFM

In the 1D-TPFM, the interaction processes between gas phase and solid propellant phase are considered and analyzed. Hence, many outputs are obtained that describe the interior ballistic process such as velocity, temperature and volume fraction of gas phase, velocity and temperature solid propellant phase [13-15]. These results are illustrated in Figs. (7-11).

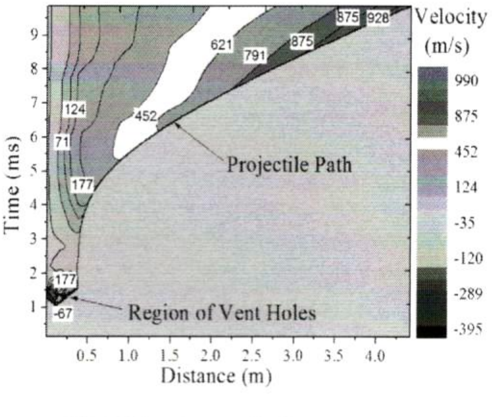

Fig.7. Gas phase velocity contours

Once the pressure at vent-holes inside the igniter reaches 20 MPa, the Vent-Holes ruptures and the flame jet flows from the igniter to the chamber penetrating the propellant at time 1.08 ms. The propellant starts the ignition at the broken vent-holes and the pressure will increase gradually inside the chamber. Once the pressure at the projectile base reaches 30 MPa, the projectile starts to move inside the bore, and the pressure continue in increasing till it reaches the maximum pressure inside the gun at time 5.4 ms, then the pressure decreases gradually until the projectile exit from the muzzle and the interior ballistic process ends.

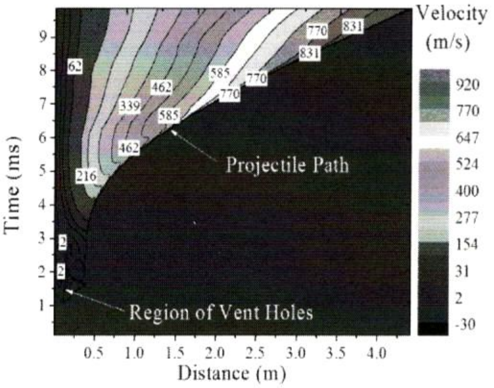

Fig.8. Solid phase velocity contours

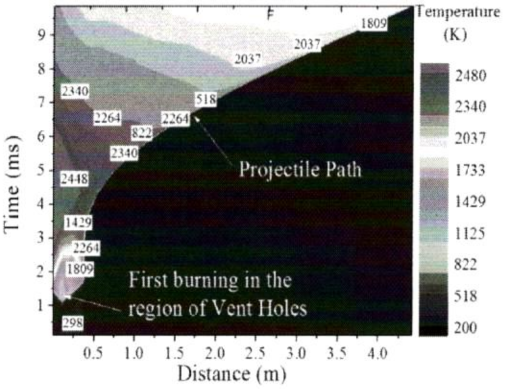

Fig.9. Gas phase velocity contours

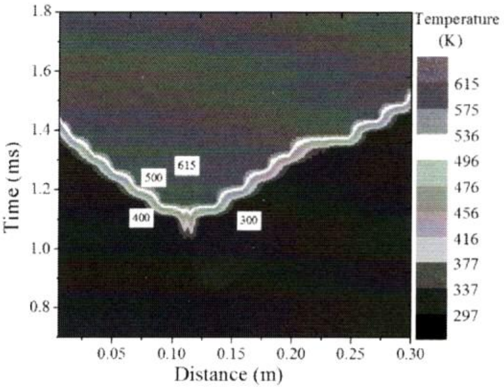

Fig.10. Solid phase velocity contours

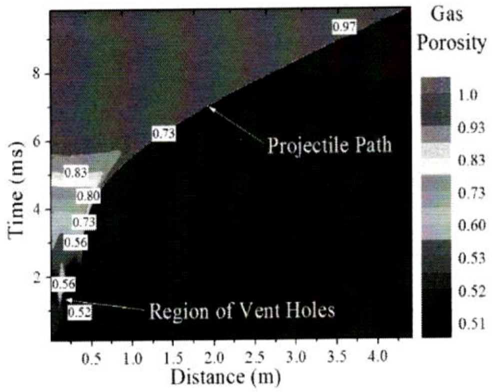

Fig.11. Gas phase volume fractions contours

5. VALIDATION OF THE SIMULATION RESULTS

The comparison between the experimental and different tools results are shown in Table 2, this table shows an acceptance and agreement between the experimental and simulation results.

Table 2, Comparison between experimental and numerical results:

IB Parameter	Maximum chamber pressure [MPa]	Muzzle pressure [MPa]	Muzzle velocity [m/s]
Experimental results	345	88	983
IBLPM-single propellant	349.2	78.96	980.54
IBLPM-mixed propellant	344.3	87.79	983.27
1D-TPFM	342.8	68.7	984.75

For IBLPM-single propellant, the peak pressure is a little higher than the experimental peak pressure. And the muzzle velocity is a little lower than the experimental one. But, after utilizing the IBLPM-mixed propellant, the peak pressure is decreased and the muzzle velocity is increased. These results explain the effect of using mixed propellant charge instead of single propellant charge. For the TPFM, as it considers the interaction effects between gas phase and solid phase, it provides more accurate results near to the experimental results. The pressure history and the muzzle velocity versus the in-bore projectile travel for the different tools are illustrated in Figs.(12-13).

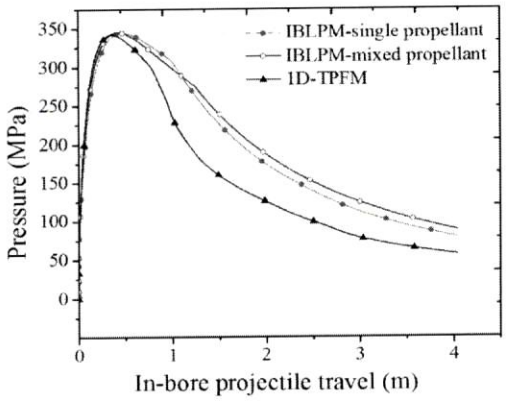

Fig.12. Pressure vs projectile displacement for different tools

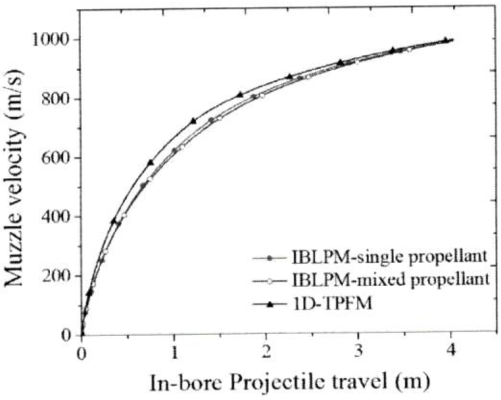

Fig.13. Pressure vs projectile displacement for different tools

6. CONCLUSIONS

In this study, three different tools for interior ballistic process, IBLPM-single propellant, IBLPM-mixed propellant and 1D-TPFM , are carried out for exploring which tool will be appropriate to couple with an optimization code to find the optimum charge design. Due to this study, it is found that:

IBLPM is simple but very useful. Hence, it is considered as the most preferred and appropriate choice for the designer regarding the following types of analysis; optimization of grain geometry, overall interior ballistic performance, performance sensitivity analysis, delayed ignition of grain perforations. Computations time on a personal computer take a few seconds for overall calculations.

The importance of the 1D-TPFM appears when the study of ignition and flame spreading is required. This code is required to analyze the pressure waves, propellant geometry, propellant location, combustion, and loading density. It provides more accurate results than the IBLPM results as it deals with the interaction between the solid propellant phase and its products (gas phase). This model has a problem, represented in some required input data are often not available for the propelling charges. Although the 1D-TPFM has a certain level of complexity, it is also an appropriate choice to couple with the optimization codes to find the optimum charge design. The computations time on a personal computer take almost 8-10 minutes for overall calculations.

The multidimensional, multiphase flow code may well be required to provide a full description of the transient, multidimensional, gas and solid-phase inside the chamber. But it has two major problem; the first problem represented in the required input data that are sometimes unavailable, the second problem represented in the computations time that take almost some days. Hence, the multiphase flow codes, 2D or 3D, are not appropriate to coupled with optimization codes.

ACKNOWLEDGEMENTS

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