Dynamic Modeling and Design of a Bulk-Loaded Liquid Monopropellant Powered Rifle

This paper presents a dynamic model of the interior ballistics of an experimental liquid propellant powered rifle. The liquid propellant powered rifle described utilizes a mixture of hydroxyl ammonium nitrate and hydrocarbon fuel to replace gunpowder typically used in such firearms. The motivation for such a development is to dispose of the need for a shell casing whereby carrying only propellant and bullets will reduce both the mass and volume per shot carried by the soldier. A first-principles dynamic model of the interior ballistics is derived as a compressible fluid power problem with the chemical liberation of heat within the chamber modeled via a condensed-phase reaction rate law. The model is used to predict the overall performance in terms of ballistic kinetic energy as well as draw design insight regarding the role of friction, chamber geometry, and the profile of chamber pressure with respect to time. Simulation results are presented as well as preliminary experimental results from a proof-of-concept device. [DOI: 10.1115/1.2977464]

1 Introduction

The motivation for this work is primarily to dispense of the brass shell casing that houses gunpowder in firearms, such as the M16-A2 military rifle, in order to lighten the ammunition load of foot soldiers. The proposed mechanism for achieving this is to replace the conventional solid propellant (gunpowder) with a liquid propellant that is a stable mixture of fuel (hydrocarbon fuel) and oxidizer (hydroxyl ammonium nitrate (HAN)). Many models have been developed in an attempt to describe the interior ballistics of liquid propellant guns. Models for regenerative liquid propellant guns (RLPGs) are numerous; one such model is that by Klingenberg et al. [1]. The regenerative guns utilized a shower-headlike piston that would inject a propellant into the chamber as the reaction proceeded. The RLPG models are useful in the analysis of regenerative applications; however, they make assumptions that are inaccurate for the bulk-loaded case. The so-called “bulk-loaded” weapon systems do not introduce a new propellant into the chamber as the reaction proceeds. One RLPG model described in Ref. [1] assumes a constant breech pressure until the time that the propellant is completely consumed. This assumption is made in lieu of a burning rate model of the propellant. The kinetic energy of the gas is also said to be proportional to the kinetic energy of the projectile. In the bulk-loaded case, the burning rate of the liquid propellant is more easily known since it is not additionally influenced by the dynamics of an RLPG injector piston, and the kinetic energy of the gas can be assumed to be zero as the gas control volume (CV) has no velocity.

Less frequent in the literature were attempts to develop interior ballistic simulations for bulk-loaded guns; however, there have been some. Finite element analysis was employed to model the liquid propellant burn rate and the dynamics of the projectile. Simulations showed that a cavity burned through the liquid propellant, accelerating toward the projectile and leaving an annulus of unburned liquid propellant along the chamber wall (see, e.g., DeSpirito [2]). An insensitivity to chamber geometry was found, this being inconsistent with experimental results.

The model presented here assumes that a liquid slug is pushed against the projectile and forms a gas/liquid interface at the rear of the liquid slug. The model does not predict an annulus of the unburned propellant left on the chamber walls, which agrees with experimental observations of no propellant residue after firing. This model will show that as chamber geometry is varied, the chamber pressure can be manipulated, as seen in prior experimental results (DeSpirito [2]). Given that a dynamic interior ballistics model that accurately couples the reaction rate of a condensed-phase reaction, the compressible gas dynamics, and the equations of motion of the projectile is missing from the published literature, the work presented here establishes such a model. This paper outlines the potential advantages of the liquid propellant approach and formulates a dynamic model of the interior ballistics. The model is then used to offer design insight and predictions regarding performance. Experimental results and observations are used to validate the model.

A conventional rifle is shown in Fig. 1. An impact primer ignites a mixture of sulfur, charcoal, and potassium nitrate or some similar mixture that is contained in a brass case. These solid pellets of propellant begin to burn rapidly, creating a high-pressure gas that pushes the projectile down the barrel. A liquid propellant approach uses the same basic concept regarding the generation of a high-pressure gas to propel a projectile, yet it allows a number of potential advantages. Among these are the following key advantages: (1) a reduction in the total mass carried per shot given that the brass casing is no longer necessary, (2) a reduction in the mass of propellant per shot given that the liquid propellant can be formulated to have a higher energy density that the solid propellant, (3) the capacity to carry more rounds per clip given that only the bullets need to occupy the clip, and (4) the potential for a variable selectable muzzle velocity (nonlethal to high power) by injecting variable amounts of the liquid propellant into the combustion chamber.

Previous work regarding liquid propellant powered weapons includes a broad research effort by the U.S. military to employ liquid propellants for large-scale artillery guns. The Crusader or Advanced Field Artillery System (AFAS) was a large-scale artillery gun (Fig. 2) that was to replace the solid propellant powered M109A6 Paladin howitzer and the older M109A2/A3 howitzer in service since 1960. There were, however, numerous problems with its design, and the program was canceled in 2002. One of the largest problems with the Crusader was the rapid reaction rate of the propellants that, if bulk loaded, would cause a pressure spike, leading to a catastrophic failure of the gun. The Crusader therefore
employed a so-called regenerative system that would inject the propellant into the chamber as the reaction proceeded in order to slow the rate of pressure buildup. This requirement led to various design complications and a complex overall system. The Crusader program was canceled in 2002.

As shown by the dynamic model presented here, the application of a liquid propellant powered weapon system on a smaller scale avoids the difficulties of overpressurization and allows a simpler bulk-loaded design. Smaller caliber weapons, such as the M16, are promising application domains given the appropriate scaling of the coupled chemical reaction rate dynamics and inertial dynamics of the projectile. Specifically, the inertia of the projectile is more appropriately matched such that the reaction rate dynamics of the bulk-loaded propellant is of an appropriate time scale to produce a pressure profile with peak pressures capable of being contained with conventional materials. Also, the projectile cross-sectional area is much smaller, allowing for a much slower reaction rate as governed in part by the cross-sectional area.

2 Merits of the Proposed System

The most compelling motivation for looking into small-scale liquid propellant powered weapons is their distinct advantage of a higher energy density (propellant based and systems level) over conventional propellant guns. This advantage manifests itself in the ammunition mass that must be carried, the volume occupied by the ammunition, and the deliverable energy stored in the propellant.

There has been a considerable amount of work done in studying the merits of various HAN-based liquid propellants for various applications. HAN has been stoichiometrically mixed with fuels such as methanol, ethanol, 1-propanol, 2-propanol, 1-butanol, hydroxyethylhydrazinium (HEHN), and glycine. These fuel candidates have varied tradeoffs. Glycine, for example, has very safe propellant properties. However, its energy content is relatively low when compared with other fuels and is additionally not very soluble in HAN. A HAN/methanol mix has much higher energy per unit mass, is a stable mixture, and is very soluble in HAN. However, methanol can be toxic if ingested or absorbed through the skin. A HAN/ethanol mixture has a somewhat higher energy density than does HAN/methanol, is very soluble in HAN, is somewhat more stable than HAN/methanol, and is nontoxic. The comparisons, dynamic model, simulation results, and experimental results presented in this paper are based on a stoichiometric mixture of 13M HAN and ethanol.

A mass-based comparison of the proposed HAN/ethanol liquid propellant powered system reveals a significant advantage over a conventional M16A2 system. The most obvious way that the mass reduction will occur is through elimination of the shell casing due to the fact that the propellant can be injected directly into the chamber. The casing amounts to nearly half of the mass of a round of ammunition in the conventional M16A2 system. Mass savings are further enhanced when considering the high mass specific energy density of the liquid propellant over powder. Experimental firing data yield a maximum value of 2205 kJ of delivered kinetic energy of the projectile per kilogram of propellant, as compared with 1215 kJ/kg for powder in a conventional M16A2 weapon. As summarized in Table 1, this implies that the mass per round for an equal kinetic energy shot with the liquid propellant system is 42% of that for the conventional M16A2 system.

A volumetric comparison also yields benefits with regard to the number of bullets that can be carried in a magazine (clip), as well as the reduced volume occupied by the propellant. Seven times the number of bullets can be placed in a magazine because of the elimination of the shell casings. Figure 3 shows a pictorial representation of this increase. Dispensing of the shell casings requires that the propellant be housed somewhere in the weapon. Candidate locations for the storage of the propellant include the hollow spaces in the handle or the stock, or both (see Fig. 1). Based on experimental data, the volumetric energy density of the proposed system is 3.05 kJ/ml (kinetic energy of the projectile per milliliter of propellant) versus 1.04 kJ/ml for the conventional M16A2 system. This implies a volumetric requirement per shot for the proposed system that is 34% of that for the conventional system.

Additional merits of the proposed system include a weapon less prone to jamming given that no ejection port or ejection mechanism is required, the potential for a variable selectable muzzle velocity (nonlethal to high power) by injecting variable amounts of the liquid propellant into the combustion chamber, and safer logistics given the transport of nonexplosive liquid containers.

3 Dynamic Model

As shown in the model presented below, the reaction rate of HAN-based combustion reactions is proportional to the cross-sectional area of the propellant chamber as well as the temperature
of the reaction product gases. Simulations of a bulk-loaded system show that the inertia and length scales of an M16 result in reasonable and appropriate pressure profiles and therefore support the notion of applying the bulk-loaded liquid propellant concept to small-scale arms.

The dynamics of the interior ballistics of the liquid propellant powered rifle can be cast as a lumped parameter model consisting of the motion dynamics of the bullet and the remaining liquid propellant, the chemical combustion rate dynamics, and an energetically based fluid power model relating the rates of change in the pressure of the combustion gases to the work done by the gases. The literature contains various models and assumptions regarding the combustion of liquid propellants in guns. As was assumed in Shaw and Williams [3] and in Vosen [4], it will be assumed here that the process results in a pocket of high-pressure combustion gases that forces the remaining quantity of the propellant up against the bullet. This assumption results in a gas/liquid interface. The formation of such an interface, along with the assumption of an incompressible liquid propellant, allows the bulk representation of the slug of the liquid propellant as a rigid body with a variable mass. The combustion rate dynamics can then be expressed in terms of the area of the gas/liquid interface and the temperature at the interface surface. An energetic balance of a CV drawn around the gas relates the enthalpy of the reaction, the pressure and temperature of the gas, and the work rate. Figure 4 shows a schematic of the process and the nomenclature used.

### 3.1 Dynamics of Motion

A free body diagram of the bullet relates the acceleration of the bullet \( \dot{v}_b \), the mass of the bullet \( m_b \), and the mass of the remaining propellant \( m_l \) to the frictional force \( F_{fric} \) produced between the bullet and the barrel, the pressure \( P \) in the gas CV that is transmitted through the propellant and pushes on the area of the bullet \( A_b \), the force from the atmospheric pressure \( P_{atm} \) applied to the front area of the bullet, and the force from the rate of change in the propellant \( m_l \) multiplied by \( \dot{v}_p \), the velocity of the fluid products of the propellant as it enters the gas CV relative to the velocity of the fluid at the interface,

\[
(m_b + m_l)\ddot{v}_b = PA_b - P_{atm}A_b - F_{fric} - m_l\dot{v}_p
\]

In Eq. (1) it will be assumed that the relative velocity of the mass departing from the liquid is equal to the velocity of the slug of the liquid propellant; this is equivalent to assuming that the liquid “deposits” gas behind the gas/liquid interface as the reaction proceeds. The velocity of the fluid particles at the gas/liquid interface can be obtained from an assumption of incompressible flow by equating volumetric flow rates near the bullet and near the interface: \( A_b\dot{v}_b = A_l\dot{v}_l \). Therefore \( \dot{v}_l = \dot{v}_b \), as expected. The dynamics of the bullet are therefore specified by

\[
(m_b + m_l)\ddot{v}_b = (P - P_{atm})A_b - F_{fric} - m_l\dot{v}_b
\]

Assuming an incompressible liquid propellant, the position of the bullet and interface can be related to the mass of the propellant,

\[
m_l = \rho_lA_l(x_b - x_{atm})
\]

Differentiation and rearrangement of Eq. (3) lead to the following expression for the velocity of the gas/liquid interface:

\[
\dot{v}_{int} = \frac{\rho_lA_l\dot{v}_b - m_l}{\rho_lA_l}
\]

Substitution of \( \dot{V} = A_l\dot{v}_{int} \) leads to an expression for \( \dot{V} \), which will be needed in the compressible fluid power model of the gas CV.

### 3.2 Combustion Rate Dynamics

The use of Eq. (2) requires that the mass consumption rates of the propellant and the pressure of the combustion gases be related to the motion dynamics of the bullet. The combustion of the propellant (a stoichiometric mixture of HAN and ethanol) can be written as the following two-step reaction:

\[
\text{NH}_2\text{OHNO}_3 + \phi \text{H}_2\text{O} \rightarrow \text{N}_2 + (\phi + 2)\text{H}_2\text{O} + \text{O}_2
\]

\[
\frac{1}{2}\text{C}_2\text{H}_5\text{OH} + \text{O}_2 \rightarrow \frac{3}{2}\text{CO}_2 + \text{H}_2\text{O}
\]

Reaction (5) is the deflagration of HAN and is the limiter to the overall reaction rate. Reaction (5) yields oxygen, which is assumed to be instantly consumed (relative to the time scale of the deflagration) by its combustion with ethanol in reaction (6). The overall reaction can be written as

\[
\text{NH}_2\text{OHNO}_3 + \phi \text{H}_2\text{O} + \frac{1}{2}\text{C}_2\text{H}_5\text{OH} \rightarrow \text{N}_2 + (\phi + 3)\text{H}_2\text{O} + \frac{3}{2}\text{CO}_2
\]

In reactions (5) and (7), \( \phi \) is dependent on the molarity of HAN used. As stated in Shaw and Williams [3], the rate of deflagration is dependent on the area of the propellant surface and the temperature at the surface. Following the model given in Shaw and Williams [3], Eq. (8) below relates the mass consumption rate of the propellant, \( \dot{m}_l \), to the area of the gas/liquid interface, \( A_p \), through a number of known constants,

\[
\dot{m}_l = -A_b\sqrt{\frac{2\rho_lR\lambda T_0^2e^{E/RT}}{EqV}}
\]

where \( \rho_l \) is the density of the liquid propellant mixture, \( R \) is the universal gas constant, \( \lambda \) is the pre-exponential factor in units of s\(^{-1} \), \( T \) is the temperature at the gas/liquid interface, \( E \) is the activation energy in units of J/mol, \( q \) is the heat of combustion per unit mass of HAN (J/kg), and \( Y_0 \) is the mass fraction of HAN in the mixture.

### 3.3 Compressible Fluid Power Model

A power balance performed on the gas CV relates the storage rate of energy to the power across the CV boundary,

\[
\dot{U} + \dot{E} = \dot{H} + \dot{Q} - \dot{W}
\]

where \( \dot{U} \) is the rate of internal energy storage in the gas (energy storage in the form of heat), \( \dot{E} \) is the rate of change in the kinetic energy of the gas (energy storage in the form of kinetic energy), \( \dot{H} \) is the enthalpy crossing the CV boundary due to the liquid propellant being converted into gas and entering the gas CV, \( \dot{Q} \) is the rate of heat entering the CV, and \( \dot{W} \) is the work rate of the CV on the external environment. In keeping with the assumption of the reaction “depositing” gas in the gas CV as the reaction proceeds (see Eq. (2)), it is assumed that the kinetic energy of the gas is zero and, therefore, that \( \dot{E} \) is zero. For the analysis presented here, it is also assumed that the heat losses of the system can be neglected (\( \dot{Q} = 0 \)). We assume as well that the rate of internal thermal energy storage can be written as

\[
\dot{U} = \dot{P}V + \dot{PV}/(\gamma - 1)
\]

where \( P \) and \( V \) are the pressure and volume of the gas CV, respectively, and \( \gamma \) is the ratio of specific heats of the products of reaction. The enthalpy rate is given by the mass flow rate of gas.
entering the CV, \( m \), the HAN mass specific heat of combustion, \( q \), and the mass fraction of HAN in the propellant mixture, \( Y_0 \),

\[
\dot{H} = m \dot{q} Y_0
\]

(11)

Applying mass conservation, the rate of change of gas in the CV is due purely to the rate of change in the liquid propellant,

\[
m = - \dot{m}_l
\]

(12)

The work rate of the gas CV is given by

\[
\dot{W} = P \dot{V}
\]

(13)

Combining Eqs. (9)–(13), the pressure dynamics of the gas CV may be written as

\[
\dot{P} = - \left( \frac{\gamma - 1}{\gamma} \right) m \dot{q} Y_0 - \gamma P \dot{V}
\]

(14)

Using the ideal gas law, the temperature of the gas CV is given by

\[
T = \frac{P V}{m \bar{R}}
\]

(15)

where \( \bar{R} \) is the gas constant of the products in units of J/(kg K).

4 Simulation Results

The dynamic model of the interior ballistics presented above was simulated numerically. The states of the dynamic system are given by \( v, P, \) and \( V \), each evolving according to Eqs. (2), (14), and (4), respectively (where \( V = A_b \dot{v} \)). These state equations are summarized below for convenience,

\[
(m_b + m_l) \ddot{v}_b = \left( P - P_{amb} A_b - F_{fric} - \dot{m}_l \dot{v}_b \right)
\]

(2’)

\[
\dot{P} = - \left( \frac{\gamma - 1}{\gamma} \right) m \dot{q} Y_0 - \gamma P \dot{V}
\]

(14’)

\[
\dot{V} = \frac{P \dot{A}_b \dot{v}_b - \dot{m}_l}{\rho_l}
\]

(4’)

A number of auxiliary equations are also necessary to relate the states of the system to more convenient variables. These auxiliary equations are summarized below for convenience,

\[
\dot{m}_l = A_b \sqrt{\frac{2 \rho R \lambda T^2 e^{-E_B T}}{E q Y_0}}
\]

(8’)

\[
\dot{m} = - \dot{m}_l
\]

(12’)

\[
T = \frac{P V}{m \bar{R}}
\]

(15’)

It should be noted that it is necessary to numerically integrate Eq. (8) to obtain \( m_l \). It should also be noted that Eq. (8) is a function of the states. The mass of gas \( m \) used in Eq. (15) is found by numerically integrating Eq. (12) where it is necessary to initialize the integration with a small initial value of gas \( m_0 \) to avoid singularities.

Table 2 shows the values of the parameters used in the simulation. The simulation was initiated by introducing an initial temperature and pressure in the initial quantity of gas \( m_0 \) to start the combustion. This initial temperature and pressure effectively model the primer. The friction was initially modeled to match the experimental setup where the lead bullet was required to extrude slightly through the bullet seat. The simulation was very insensitive to the magnitude of this friction modeling, and it was subsequently neglected. Figure 5 shows the pressure in the chamber as a function of time. It should be noted that although the pressure reaches a higher pressure than a conventional M16A2 weapon, it is still within reasonable bounds for standard gun materials. Figure 6 shows the temperature as a function of time, and Fig. 7 shows the velocity of the bullet and the velocity of the interface as a function of time. Figure 8 shows the mass of the propellant as it reacts. Simulation results yielded a mass specific energy density of 1770 kJ/kg of propellant and a volumetric energy density of 2.45 kJ/ml of propellant. Gunpowder in conventional weapons has a mass specific energy density of about 1215 kJ/kg and a volumetric energy density of about 1.04 kJ/ml.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_b )</td>
<td>Bullet mass</td>
<td>5.5 g</td>
</tr>
<tr>
<td>( l_b )</td>
<td>Barrel length</td>
<td>0.53 m</td>
</tr>
<tr>
<td>( A_b )</td>
<td>Cross section of the barrel</td>
<td>24.63 cm²</td>
</tr>
<tr>
<td>( m_0 )</td>
<td>Initial propellant mass</td>
<td>2.63 g</td>
</tr>
<tr>
<td>( \rho_l )</td>
<td>Propellant density</td>
<td>1384 kg/m³</td>
</tr>
<tr>
<td>( B )</td>
<td>Pre-exponential factor</td>
<td>( 3.1 \times 10^{10} ) s⁻¹</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Propellant thermal conductivity</td>
<td>0.51 W/(m K)</td>
</tr>
<tr>
<td>( q )</td>
<td>Heat of combustion</td>
<td>5892 kJ/kg</td>
</tr>
<tr>
<td>( Y_0 )</td>
<td>HAN mass fraction</td>
<td>0.7484</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Ratio of specific heats</td>
<td>1.33</td>
</tr>
</tbody>
</table>

![Fig. 5 Pressure in the chamber](image)

![Fig. 6 Temperature in the chamber](image)
5 Experimental Results

An experimental prototype of a liquid propellant powered rifle was constructed and tested. A stoichiometric mixture of 13M HAN and ethanol was used as the propellant mixture. All physical parameters were matched by the simulation such that a comparison could be made. Figure 9 shows a photograph of the disassembled prototype. The prototype has a rifled 0.22 in. diameter, 18 in. long barrel similar to that used in an M16A2. The barrel, the bullet seat, and the combustion chamber carrier assemble together, using the barrel flange and the assembly collar, with chamfered surfaces to promote adequate sealing. The top of the combustion chamber carrier contains a seat for a standard small rifle primer, which is initiated by a firing pin that is spring loaded in the firing/trigger mechanism. Figure 10 shows a schematic of the experimental prototype.

The prototype was loaded with a 5.5 g lead bullet and 2.6 g of HAN/ethanol propellant mixture and was fired several times. The muzzle velocity was measured with a GM Kemmer Competition Electronics Digital Pro Chrono chronograph. Table 3 shows the firing data obtained from the prototype.

Although the experimental prototype fired every time it was loaded, the measured muzzle velocities were inconsistent. It was observed that for the lower velocity shots, a small amount of liquid propellant residue remained in the firing chamber. For the highest velocity shots, the firing chamber was dry and clear of any propellant residue. One possible cause of this variation is inconsistent sealing of the chamfered pieces. Other possible causes include inaccuracy in the mixture, given the small amount used. Sealing is admittedly a potential challenge for a caseless ammunition liquid propellant rifle. In a conventional weapon, the brass casing opens up and forms a seal with the barrel. With the liquid propellant rifle, a seal must be formed without the help of a casing.

The muzzle velocity obtained from the simulation was 1300 m/s, which was in good agreement given the sources of error stated above with the two highest muzzle velocities obtained with the experimental prototype in cases where no propellant residue was present. The highest muzzle velocity results in a mass specific energy density of 2205 kJ/kg and a volumetric energy density of 3.05 kJ/ml. These compare favorably with the numbers of 1215...
kJ/kg and 1.04 kJ/ml for a conventional M16A2 system and serve to support the proposed advantages of a liquid propellant-based rifle system.

6 Variable Area Dynamic Model

As mentioned above, the reaction rate of HAN-based combustion reactions is proportional to the area of the gas/liquid interface. In the previous model, the area of the chamber was equal to that of the barrel. However, the fact that the reaction rate is proportional to the cross-sectional area of the interface can be made advantageous. There are several possible gains that can be made by choosing a variable cross-sectional area profile for the chamber. A capability to relieve the initial pressure spike seen in Fig. 5 may be possible, allowing for lighter gun materials. Also, varying of the chamber cross-sectional area may allow stretching or shortening the duration of the pressure profile to fit a desired barrel length. Figure 11 shows a profile type that was tested in simulation. The initial bullet position is shown as \( x_b^0 \), and the chamber geometry is tapered from an initial diameter of \( d_i \) to the barrel diameter at \( x_b^0 \) such that all simulations contain equal volume and mass of propellant.

Referring to Eq. (1), the force balance on the bullet remains the same. The velocity of the fluid particles at the liquid/gas interface can again be obtained from an assumption of incompressible flow by equating volumetric flow rates near the bullet and near the interface,

\[
v_p = \frac{A_b}{A_{int}} v_b
\]

where \( A_{int} \) is the area of the liquid/gas interface. Combining Eqs. (1) and (16) results in the following expression for the motion dynamics of the bullet:

\[
(m_b + m_l)\dot{v}_b = (P - P_{atm})A_b - \frac{A_b}{A_{int}} m_l \dot{v}_b - F_{fric} - \frac{A_b}{A_{int}} m_l v_b
\]

Again, assuming an incompressible liquid propellant, the position of the interface can be related to the position of the bullet and the mass of the propellant,

\[
\frac{m_l}{\rho_l} = A_b(x_b - x_b^0) + V_l(x_{int})
\]

where \( V_l(x_{int}) \) is the volume of liquid still in the conical section of the chamber (right frustum of a cone) and is a geometric function of the position of the interface. Rearranging Eq. (18) and inverting the \( V_l \) function result in the position of the gas/liquid interface, which in turn yields the gas volume, which will again be used in Eqs. (14) and (15). The mass flow rates and the pressure evolve as specified by Eqs. (8), (12), and (14).

7 Variable Area Simulation Results

The parameter values in Table 2 were used for the variable area simulations with the additional parameter, \( d_i \). This initial diameter of the chamber, as shown below, affects various simulation results. Figure 11 shows \( d_i \), which is varied to form different profiles. Figure 12 shows the pressure in the gas control volume

### Table 3 Firing data from the experimental prototype

<table>
<thead>
<tr>
<th>Shot no.</th>
<th>Velocity (ft/s)</th>
<th>Velocity (m/s)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>4761</td>
<td>1451.2</td>
</tr>
<tr>
<td>2</td>
<td>2879</td>
<td>877.5</td>
</tr>
<tr>
<td>3</td>
<td>1799</td>
<td>548.3</td>
</tr>
<tr>
<td>4</td>
<td>2275</td>
<td>693.4</td>
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<td>5</td>
<td>2196</td>
<td>669.3</td>
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<tr>
<td>6</td>
<td>2275</td>
<td>693.4</td>
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<td>7</td>
<td>1450</td>
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<td>8</td>
<td>4678</td>
<td>1425.9</td>
</tr>
<tr>
<td>9</td>
<td>3555</td>
<td>1083.6</td>
</tr>
</tbody>
</table>
Some interesting results arise from changing the pressure profile. As was suspected intuitively, the maximum pressure can be manipulated significantly by changing the chamber profile. Figure 12 shows that by changing $d_i$ from 5.56 mm to 2 mm, the maximum pressure lowers from about 1500 MPa to less than 1400 MPa. By taking the initial diameter down to its practical limit of 0.1 mm, a vast reduction in peak pressure is seen as the maximum reaches only about 500 MPa. As shown in Fig. 13, the propellant burns much more slowly as the initial diameter is decreased, as predicted by Eq. (8). The advantage of this phenomenon is that while peak pressures can be reduced to a third of the straight profile case, the resulting final velocity remains practically unchanged. Because of this, it is possible to reduce the wall thickness of the weapon, thereby allowing the soldier to carry more or to move faster. Figure 14 shows the temperature in the gas control volume.

8 Conclusions

A first-principles dynamic model of a liquid propellant powered rifle was presented. This model incorporates a deflagration rate model of HAN-based reactions and treats the problem as a dynamic compressible fluid power problem. A simulation of this model was performed and compared with firing data from an experimental prototype that was constructed. The experimental setup showed a significant variation in the muzzle velocity but did fire reliably. The higher experimentally measured muzzle velocities agreed well with the simulated dynamic model and support the merits of such a propellant powered rifle over a conventional M16A2 rifle. These merits include (1) a reduction in the total mass carried per shot, (2) a reduction in the mass of the propellant per shot, (3) the capacity to carry more rounds per clip, (4) a weapon potentially less prone to jamming, (5) the potential for a variable selectable muzzle velocity (nonlethal to high power), and (6) safer logistics given the transport of nonexplosive liquid components.

The dynamic model can additionally be used to draw design insights regarding the liquid propellant powered rifle design. Given that the deflagration rate controls the combustion rate and is a function of the cross-sectional area of the combustion chamber, the dynamic model suggests that an area profile, i.e., not a constant as a function of $x$, could be designed to better control the combustion rate and therefore the pressure profile in the gun. Simulations also show that pressure peaks can be greatly reduced by varying the chamber geometry while the muzzle velocity remains practically unchanged (Fig. 15). The dynamic model also allows the investigation of other fuel candidates to be mixed with HAN, such as the nearly universal U.S. military fuel JP-8.

The liquid monopropellant rifle has several positive aspects to it. However, it presents some challenges relative to conventional rifles. First, sealing is an issue. With a conventional M16A2 rifle, the bullet is sealed by the brass casing as the casing is crimped around the bullet. Upon firing, the casing opens up and seals against the barrel walls. In simulation, where sealing is not an issue, the propellant burns up 28 cm from the initial bullet position. This means that in theory, a good seal (very tight tolerances) would need to be held for that distance to get full combustion. Also in a conventional M16, with the ejection of the casing comes an ejection of heat. In the liquid propellant “caseless” scenario, one must either release the heat some other way or prove that injection of a propellant into high temperature chambers is acceptable. Time for injection is also an issue, as is activation energy.

Present rifles use primers as were used in this liquid propellant experimentation; however, this seems like an unlikely choice for rapid fire since there would need to be some mechanism to eject and replace the primer. Electrical ignition is one possible solution; however, it may have combat reliability problems leading to its rejection.

Implementation of the variable area model reveals other issues.
One is that to keep the volume constant for various profiles, one must make the chamber longer to keep the same volume for small $d_i$. This could possibly create the need for a longer gun. The variable area model is a valuable tool, but as with any untested model it should be looked at with some caution. The next step would be to machine a chamber with a smaller initial diameter, to test its muzzle velocity, and to implement pressure sensors along its length.

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References


