Analysis of Inter-Chamber Energy and Mass Transport in High-Low Pressure Gun Systems

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Two assumptions are often made by lumped-parameter codes in the analysis of dual-chamber guns: (1) that the gas enters the large chamber at the propellant flame temperature, and (2) that the flow between the chambers is that of an ideal gas. An investigation on the effects of these two assumptions was performed by creating three lumped-parameter codes: one that maintains the two assumptions above, and two that conserve flow energy of the gas instead of maintaining a constant temperature. Of the latter two models, one uses an ideal gas and the other uses a noble-abel gas for the flow calculations. In this work, the noble-abel gas equation of state will be discussed in detail as well as its implications to the gas flow. Then, descriptions of the three approaches to the gas flow model will be presented, followed finally by a comparison of simulation results from the three models.

Introduction

In certain interior ballistics applications, it is desirable for a relatively low pressure to be applied to the projectile base, which may be due to the projectile's sensitivity to high accelerations or a design objective that requires a projectile with a low muzzle velocity. This problem is often solved by using a dual-chamber high-low pressure gun. In such a system, the propellant (or at least a portion thereof) is contained in a small chamber, where it burns reliably and consistently under a high pressure. Then the reaction products are vented into a larger chamber where they apply a lower pressure to propel the projectile [1].

While recent work has led to sophisticated multi-dimensional and multi-phase flow models in interior ballistics [2,3], an inherent value remains with the lumped-parameter codes, which predict peak pressure, muzzle velocity, and action time to within a reasonable accuracy while maintaining much faster program run times. Pressure, velocity and action time are of great importance to any modeling effort because they can be measured relatively easily in test firings and are typically used to qualify and evaluate the performance of a weapon. It is therefore desirable to continue the development of the zero-dimensional lumped-parameter codes.

One of the best known lumped-parameter codes which handles high-low pressure guns is the HILO [4] extension for IBHVG2 [5], which utilizes compressible flow equations [6] to simulate the gas flow from the high-pressure chamber into the low-pressure chamber. HILO also allows solid propellant grains (if small enough) to pass through the vents between the two chambers along with the gas.

The objective of this work is to investigate the effects of two simplifications made by lumped-parameter dual-chamber gun models similar to HILO regarding the energy and mass flow between the two chambers. The first is that the temperature of the gas in the small chamber as well as the gas flowing in the vents is always equal to the propellant flame temperature. To accurately conserve energy in transferring the gas, however, the sum of the enthalpy and the kinetic energy of the gas should remain constant [7] rather than the gas temperature; the mean temperature in the high-pressure chamber can then be calculated using energy conservation equations instead of remaining equal to the propellant flame temperature.

The second simplification is that the gas flow between the chambers is based on that of an ideal gas. The Noble-Abel equation of state is very commonly used in interior ballistics models (including IBHVG2 and HILO) to calculate the space-mean pressure in the chambers; for consistency, it seems appropriate to also use this equation of state in calculating the mass flow rate and the associated energy of the gas which is exchanged between the two chambers.

The investigation of these two simplifications was performed by creating a computer program which is very similar to IBHVG2 with the HILO extension (the actual source code for IBHVG2 was not available), in which three different subroutines were used for the portion of the program which handles the mass and energy flow between the two chambers. The first subroutine uses the aforementioned assumptions made by HILO, the second calculates the gas temperature by conserving the flow energy of an ideal gas, and the third calculates the gas temperature by conserving the flow energy of a Noble-Abel gas.

In this work, the Noble-Abel gas equation of state will first be discussed and compared with the ideal gas equation of state, including the necessary equations used in the program. Then, descriptions of the three approaches to the gas flow will be presented, including the method of calculating the mean temperature in the two chambers. Finally, simulation results for a representative 120-mm mortar will be presented and compared among the three models.

The Noble-Abel Gas

The ideal gas equation of state $Pv = RT$ (where P is the pressure, v is the mass-specific volume and equals $1/\rho$, R is the specific gas constant, and T is the temperature) is a good approximation for many gases near standard ambient conditions. In interior ballistics situations, however, the gas density and temperature are usually very high, and a better approximation is the Noble-Abel equation of state:

$$P(v - \eta) = RT , \qquad (1)$$

where η is the gas covolume. This idea is similar to that of the van der Waals equation of state, but without the attractive intermolecular forces—the high temperature causes the kinetic energy of the gas to greatly exceed the intermolecular potential energy [8], so the attractive forces become negligible.

In order to utilize the Noble-Abel equation of state to calculate the mass and energy transfer between the two chambers, certain relationships must first be established regarding isentropic compressible flow of the gas. In this section, the thermodynamic and compressible flow properties of the Noble-Abel gas are discussed, as well as the implications to the interior ballistics model. As expected, each equation pertaining to the Noble-Abel gas approaches that of an ideal gas as $\eta \rightarrow 0$.

Isentropic Processes and the Speed of Sound

In this work, isentropic processes are those which are both adiabatic and reversible [6]. If γ is defined as the ratio of the specific heat at constant pressure c_p to the specific heat at constant volume c_v, then a Noble-Abel gas undergoing an isentropic change maintains the following relationship between pressure and volume [8]:

$$P(v - \eta)^{\gamma} = \text{constant}, \qquad (2)$$

assuming that c_p, c_v and η are all constant.

Now, if a Noble-Abel gas exists in a thermodynamic state "1" with properties $\{P_1, T_1, v_1\}$ and state "2" with properties $\{P_2, T_2, v_2\}$, then equations (1) and (2) can be used to obtain the set of isentropic relations:

$$\frac{P_2}{P_1} = \left(\frac{v_2 - \eta}{v_1 - \eta}\right)^{-\gamma} = \left(\frac{1/\rho_2 - \eta}{1/\rho_1 - \eta}\right)^{-\gamma} = \left(\frac{T_2}{T_1}\right)^{\gamma/(\gamma-1)} . \qquad (3)$$

Next, the speed of sound c in a gas is related to the isentropic change in pressure with respect to temperature, which for the Noble-Abel gas is [8]:

$$c = \sqrt{\frac{\partial P}{\partial \rho}} = \frac{1}{1-\rho\eta}\sqrt{\gamma RT} = \sqrt{\frac{\gamma P}{\rho(1-\rho\eta)}} . \qquad (4)$$

The analogous isentropic relations and the speed of sound for an ideal gas are [6]

$$\frac{P_2}{P_1} = \left(\frac{v_2}{v_1}\right)^{-\gamma} = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma} = \left(\frac{T_2}{T_1}\right)^{\gamma/(\gamma-1)} , \qquad (5)$$

and

$$c = \sqrt{\gamma RT} = \sqrt{\gamma P/\rho} . \qquad (6)$$

Enthalpy

The specific enthalpy h of a gas is its specific internal energy u plus the work term Pv that would be required to make space for the gas to exist in the surrounding environment [9]. Since $R = c_v(\gamma - 1)$ [8], then equation (1) can be used to express the specific enthalpy of the Noble-Abel gas as

$$\begin{aligned} h &= u + Pv \\ &= u + c_v(\gamma - 1)T + P\eta . \end{aligned} \tag{7}$$

In this problem, the convention has been chosen that $u = 0$ when $T = T_\infty$. Assuming a constant value for c_v, the specific internal energy of the gas is

$$u = c_v(T - T_\infty). \tag{8}$$

With this convention, the specific enthalpy of the Noble-Abel gas can be written as

$$h = c_v(\gamma T - T_\infty) + P\eta . \tag{9}$$

The specific enthalpy of an ideal gas is

$$h = c_v(\gamma T - T_\infty). \tag{10}$$

Compressible flow

The one-dimensional isentropic compressible flow model relates the thermodynamic state of a moving gas to its velocity via a consideration of energy conservation along the flow path [6]. Neglecting gravitational potential energy, the total energy of the gas is its internal energy, kinetic energy, and the work done to create space for the gas to exist. If, however enthalpy is tracked instead of the internal energy, then the flow work is automatically accounted for [7]. In this section, let the subscript 0 represent the conditions of the gas at rest (velocity $\upsilon = 0$). The desired result here is to obtain the total temperature T_0 of the Noble-Abel gas relative to its static temperature T as a function of the Mach number M. Beginning with the energy conservation equation for the gas flow,

$$h + \frac{\upsilon^2}{2} = h_0 , \tag{11}$$

plug in (9) for the specific enthalpy, and cancel the T_∞ terms from both sides. Next, use the isentropic relations (3) to eliminate the term P_0, and make the substitutions $c_v = R/(\gamma - 1)$ [8] and $\upsilon^2 = M^2c^2$.

What remains is an equation which is nonlinear in T_0/T, and there is no exact solution. However, for an ideal gas, the result is known (14), which is advantageous here. The Mach number is bound by $0 \le M \le 1$, and the ratio of specific heats for interior ballistics applications nearly always lies between $1.2 \le \gamma \le 1.4$. For an ideal gas, this restricts the temperature ratio to $1 \le T_0/T \le 1.2$. Therefore, provided that the covolume effects are small ($\eta << v$), the error introduced by a first-order Taylor series approximation about the point $T = T_0$ is small. Finally, substituting the speed of sound from (4) leads to the temperature ratio for the Noble-Abel gas:

$$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2(1 - \rho\eta)} M^2 . \tag{12}$$

Using the isentropic relations (3), there is a corresponding pressure ratio, and since the maximum value for M to take is 1, the flow becomes choked when the pressure ratio satisfies the condition

$$\frac{P_0}{P} \ge \left(1 + \frac{\gamma - 1}{2(1 - \rho\eta)}\right)^{\gamma/(\gamma - 1)} . \tag{13}$$

The analogous temperature ratio and choked flow condition for an ideal gas are respectively [6]

$$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M^2 , \tag{14}$$

and

$$\frac{P_0}{P} \geq \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} . \tag{15}$$

Three Approaches to Mass and Energy Flow

Three computer codes were written to perform the simulations described in this work. The three programs were identical with exception to the two subroutines which calculated the gas mass flow between the two chambers and the energy associated with that flow. This section describes the manner in which the three models treat the mass and energy flow terms.

Constant Temperature

The first model calculates the mass and energy flow between the two chambers in a manner very similar to that described in the HILO [4] module for IBHVG2. Two assumptions made are that (1) the gas temperature in the high-pressure chamber is always equal to the mean propellant flame temperature in that chamber, and (2) that the gas flowing through the vents does so at the mean propellant flame temperature. It is noted that Anderson [4] does not explicitly discuss the energy of the flow; but in this present work, the way to maintain the mean flame temperature in the high-pressure chamber is to base the flow energy solely on the internal energy of the gas leaving the chamber.

The approach to calculate the mass flow rate begins with determining whether the flow is choked via (15), which occurs whenever the condition

$$\frac{P_h}{P_l} \geq \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \tag{16}$$

is met, where the subscripts *h* and *l* indicate conditions in the high- and low-pressure chambers, respectively. If the flow is choked, then the Mach number $M = 1$, and the pressure in the throat P_τ is

$$P_\tau = P_h\left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)} . \tag{17}$$

If the condition in (16) is not met, then the flow is less than choked, and the pressure in the throat is assumed to reach the outside value ($P_\tau = P_l$). In this case, the Mach number $M < 1$, and is calculated via the temperature ratio (14) and the isentropic relations (5):

$$M^2 = \frac{2}{\gamma-1}\left(\left(\frac{P_h}{P_\tau}\right)^{(\gamma-1)/\gamma} - 1\right). \tag{18}$$

For either case of choked or unchoked flow, the gas velocity υ is the Mach number times the speed of sound (6), and the gas density in the throat ρ_τ is calculated from the ideal gas equation of state:

$$\upsilon = M\sqrt{\gamma R T_f} , \quad \text{and} \quad \rho_\tau = \frac{P_\tau}{R T_f} , \tag{19}$$

where T_f is the mean flame temperature of all propellants currently burning. Then the mass flow rate $\dot{m}$ is calculated using these velocity and density values in the continuity equation

$$\dot{m} = G \rho_\tau A \upsilon , \tag{20}$$

where *A* is the throat area, and *G* is the gas discharge coefficient [4].

When any amount of gas Δm moves between the two chambers, it carries with it a flow energy ΔE_f. The only way that the temperature in the high-pressure chamber can remain equal to the propellant flame temperature is for the flow energy to contain only the internal energy (8) of the gas which leaves. So for this constant-temperature model, the flow energy is calculated at each time step as

$$\Delta E_f = \Delta m \, c_v \left(T_h - T_\infty\right), \tag{21}$$

The method used by HILO [4] to calculate the mean gas temperature in the two chambers was not explicitly stated, although for this present work it was assumed to be similar to that of Baer and Frankle [11]. There is a fundamental difference for the dual-chamber model, however, in that neither chamber is a closed system—energy is exchanged between the two. Therefore, unlike the single chamber model [11], all energy terms must be monitored incrementally at each time step.

The change in internal energy of the gas in the high-pressure chamber at each time step is set equal to the difference between the energy released by burning the propellant in that chamber and the flow energy that leaves the chamber. The calculation in the low-pressure chamber follows the same methodology, except that losses are included as described in IBHVG2 [5], and the flow energy is added to the chamber instead of removed from it.

Constant Enthalpy of an Ideal Gas

The second model created for this analysis is also based on that presented by Anderson [4], with the exception of the two constant-temperature assumptions. It is referred to as a *constant-enthalpy* model because of the fact that the specific enthalpy of the gas in the high-pressure chamber is unaffected by the gas flow. The model still begins by determining whether the flow is choked using (16). If so, then the Mach number M = 1, and the throat pressure is obtained from (17), but the temperature in the throat is now calculated using (14) instead of assuming the same value as the flame temperature:

$$T_\tau = T_h \frac{2}{\gamma + 1}. \tag{22}$$

For unchoked flow, the throat pressure equals that in the large chamber, and the throat temperature and the Mach number are obtained from equations (5) and (14):

$$T_\tau = T_h \left(\frac{P_\tau}{P_h} \right)^{(\gamma - 1)/\gamma}, \tag{23}$$

and

$$M^2 = \frac{2}{\gamma - 1} \left(\frac{T_h}{T_\tau} - 1 \right). \tag{24}$$

The gas velocity υ and density ρ_τ in the throat are calculated using the same methods as in the previous section, but the newly calculated throat temperature T_τ is used in place of the propellant flame temperature T_f:

$$\upsilon = M\sqrt{\gamma R T_\tau}, \quad \text{and} \quad \rho_\tau = \frac{P_\tau}{R T_\tau}, \tag{25}$$

and the mass flow rate $\dot{m}$ is calculated using (20).

For this model, the flow energy ΔE_f contains the total energy of the gas leaving (enthalpy from (10) plus kinetic energy) rather than just the internal energy:

$$\Delta E_f = \Delta m \left(c_v \left(\gamma T_\tau - T_\infty \right) + \upsilon^2/2 \right) = \Delta m \, c_v \left(\gamma T_h - T_\infty \right). \tag{26}$$

As seen in (11), the flow energy can be measured either in the throat or at rest in the high pressure chamber. The program created for this analysis calculates both forms shown in (26), where the first value is used in the subsequent calculations and the second is used as an accuracy check only.

Constant Enthalpy of a Noble-Abel Gas

The methods used to conserve the total energy of the flow in this third and final model are the same as those used in the second. This time, however, the Noble-Abel equation of state is used for the gas flow calculations. One consequence of using the Noble-Abel model is that the temperature ratio (12) is dependent on the gas density in the throat, which is only known up to the previous time step. Therefore, a cubic extrapolation is used to predict the density ρ_τ^* initially, and iterative corrections are made as necessary, which will be discussed momentarily.

For the Noble-Abel gas, the choked-flow condition (13) is

$$\frac{P_h}{P_l} \geq \left(1 + \frac{\gamma - 1}{2(1 - \rho_\tau^* \eta)}\right)^{\gamma/(\gamma-1)} . \tag{27}$$

If the flow is choked, the Mach number $M = 1$, and equations (12) and (3) are used to calculate the throat temperature and pressure:

$$T_\tau = T_h \left(1 + \frac{\gamma - 1}{2(1 - \rho_\tau^* \eta)}\right)^{-1} , \tag{28}$$

and

$$P_\tau = P_h \left(1 + \frac{\gamma - 1}{2(1 - \rho_\tau^* \eta)}\right)^{-\gamma/(\gamma-1)} . \tag{29}$$

When the flow is less than choked, the pressure in the throat equals that in the large chamber, the throat temperature is calculated using (23), and the Mach number is calculated via (12):

$$M^2 = \frac{2(1 - \rho_\tau^* \eta)}{\gamma - 1}\left(\frac{T_h}{T_\tau} - 1\right). \tag{30}$$

Before continuing the calculation, the program checks for consistency by evaluating the throat density obtained from the Noble-Abel equation of state using the newly calculated values of pressure and temperature in the throat. If necessary, the solution is iterated beginning with (27) until the newly calculated density ρ_τ is within a predefined relative error tolerance (set to 10^{-6} for this present work) of the prediction ρ_τ^*.

Once the correct density is known, the program continues by calculating the gas velocity from (4):

$$\upsilon = \frac{M\sqrt{\gamma R T_\tau}}{1 - \rho_\tau \eta} . \tag{31}$$

The mass flow rate is calculated using (20), and the method of calculating the flow energy ΔE_f is the same as for the second model, except that the enthalpy term is that of a Noble-Abel gas (9):

$$\Delta E_f = \Delta m \left(c_v\left(\gamma T_\tau - T_\infty\right) + P_\tau \eta + \upsilon^2/2\right) = \Delta m \left(c_v\left(\gamma T_h - T_\infty\right) + P_h \eta\right). \tag{32}$$

Comparison of Results

In order to observe the effects of the constant-temperature and ideal-gas-flow assumptions, simulations were performed on a mortar as described by Anderson in Appendix F of [4]. In this case, the igniter serves as the high-pressure chamber, and the mortar tube bore serves as the low-pressure chamber. A condition with zero external propellant increments is considered, i.e. all of the propellant is contained in the igniter, because the influence of external propellant increments would far exceed the differences between the three models discussed herein. The simulation begins with a small primer which is all burnt at $t = 0$ to ignite the propellant.

Schmidt, Nusca and Horst [10] state that Anderson's model represents a generalized version of the 120-mm M934 mortar. Therefore, while the comparison among the results of the three models is useful, the results in this example are not expected to match experiment.

The results between the two constant-enthalpy models are much closer to each other than to the constant-temperature model, which indicates that the conservation of energy in the gas flow is of greater significance than the equation of state used to model the flow.

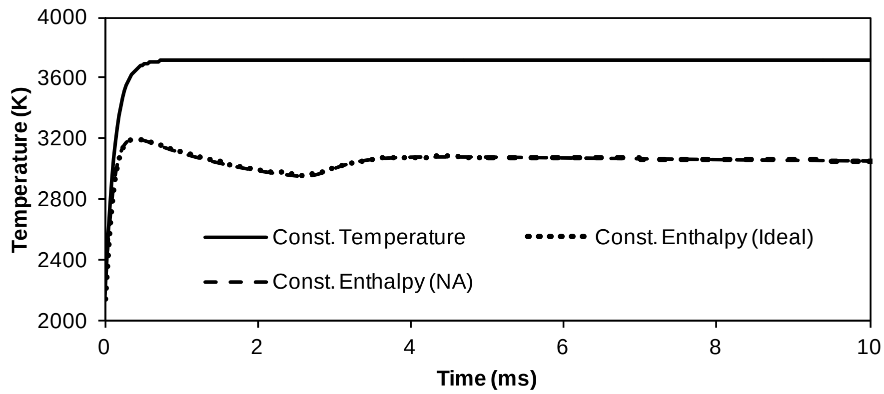

Figure 1. Mean gas temperature in igniter vs. time.

The most direct impact on the calculations is the mean gas temperature in the igniter, as shown in Figure 1. It is noted that the mean temperature in the first model is not necessarily a constant value, but it is always equal to the weighted-average of the flame temperatures of all propellant gases in the system. In this case, the gas is initially at the flame temperature of the primer, 2380 K, and then asymptotically approaches the propellant flame temperature of 3720 K. The two constant-enthalpy models demonstrate a peak igniter temperature just below 3200 K, followed by a cooling period during the main gas discharge until $t \approx 3$ ms, and then the temperature asymptotically approaches 3020 K. By its very nature, the constant-temperature model does not reproduce the temperature drop observed in the two constant-enthalpy models, which is due to the fact that only the internal energy of the gas is considered and not the total energy. Therefore, at each time step, energy is not conserved along the flow path, and the flow energy term ΔE_f in the constant-temperature model is approximately 19 percent too small when compared with the upstream enthalpy of the gas.

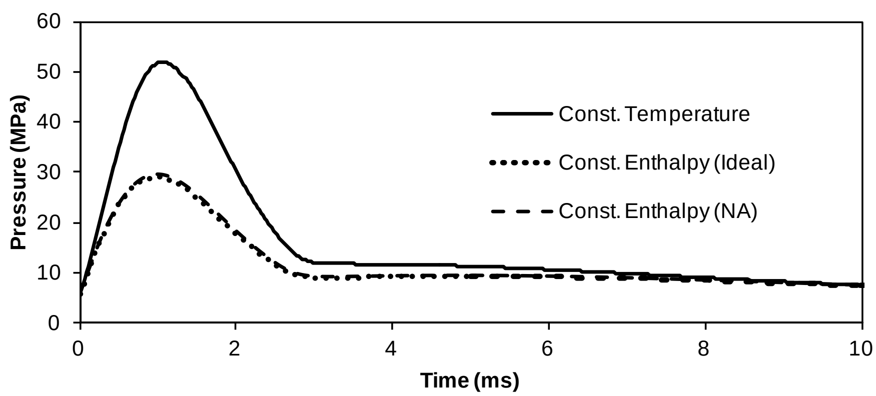

Figure 2. Mean gas pressure in igniter vs. time.

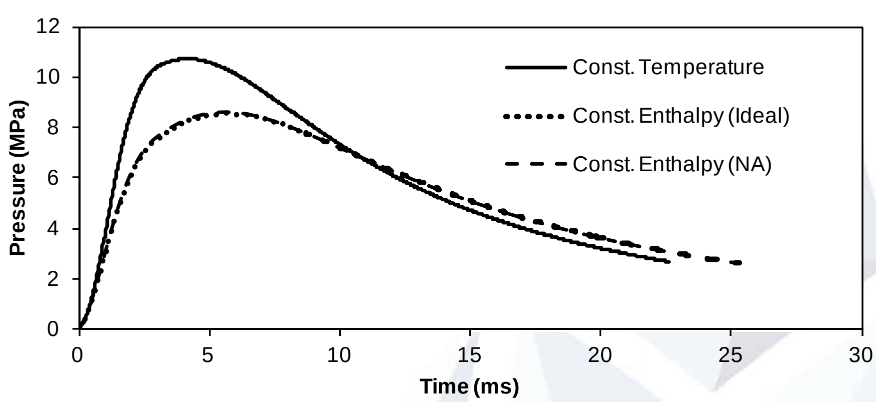

Figure 3. Breech pressure vs. time.

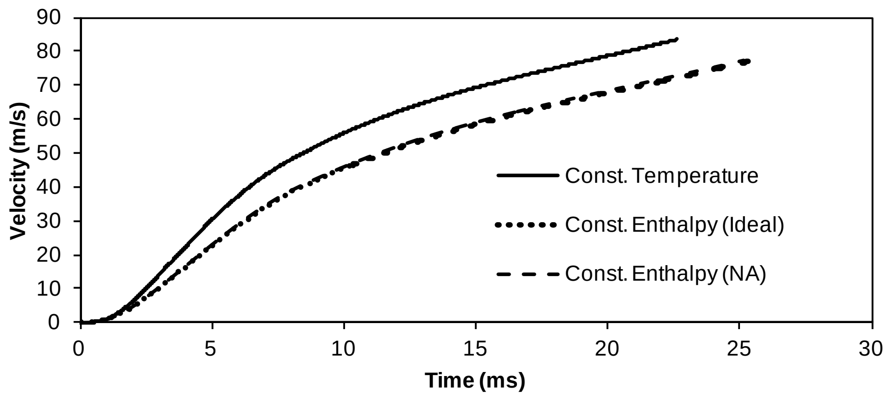

Figure 4. Projectile velocity vs. time.

Model	Peak Breech Pressure (MPa)	Peak Igniter Pressure (MPa)	Projectile Velocity (m/s)	Action Time (ms)
Constant Temperature	10.72	51.92	83.43	22.62
Constant Enthalpy (Ideal)	8.55	29.06	76.90	25.29
Constant Enthalpy (NA)	8.64	29.67	77.18	25.16

Table I. Summary of Pressure, Velocity and Action Time Results

The next major difference between the constant-temperature and constant-enthalpy models is the pressure in the igniter, which is plotted in Figure 2. This difference stems from the gas equation of state, since the gas pressure is proportional to its temperature. These increased values of temperature and pressure lead to a higher mass flow rate of the gas into the bore, which in turn causes a higher peak breech pressure and muzzle velocity, and a shorter action time in the constant-temperature model than in the two constant-enthalpy models, as shown in Figures 3 and 4. Table I lists the peak pressure in each chamber, as well as the projectile velocity and action time for each of the three models.

Conclusion

The most important conclusion of this work is the observation that applying energy conservation principles to the gas flow between the high- and low-pressure chambers made a substantial impact on the results of the interior ballistics simulation in terms of the predicted peak pressures, muzzle velocity, and action time. Once these conservation principles are in use, at least for the example case considered, the difference between the flow of a Noble-Abel gas and that of an ideal gas is less pronounced.

The differences between the two equations of state would be accentuated if the propellant reaction product gas had a larger covolume or reached a higher density. The covolumes for the gases used in these examples were approximately 10^{-3} m^3/kg, which is typical in ballistics applications since the gases are combustion products consisting of small molecules. Due to the term $(1 - \rho\eta)$ in so many of the equations for the Noble-Abel gas, the covolume will begin to make more of an impact when the gas density is increased; the pressures inside high-velocity rifles and cannons can reach 400–500 MPa, which result in much higher gas densities than that which was observed in the example calculations herein. However, dual-chamber systems are counter-productive to achieving such velocities, so this scenario may be unrealistic.

It is therefore likely that the constant-enthalpy model using the ideal gas equation of state for the gas flow between chambers is a sufficient lumped-parameter model for dual-chamber guns. This model is an improvement over existing models because it conserves energy along the flow path and can therefore provide more accurate predictions of the key pressure, velocity, and action time results without the unnecessary complexities introduced by the Noble-Abel gas flow calculations.

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