A performance of the interior ballistics according to the position of the solid propellant in the chamber has been investigated using the IBcode. In previous researches, propellants have been evenly distributed in the chamber. In this study, however, three cases of the existence of empty space in the chamber at which the propellants are not evenly distributed are considered. The case of the propellant located in the region near the base and breech has shown that the negative differential pressure and the difference between the breech pressure and the base pressure are much higher than those of the case of the propellant located in the center of the chamber. The case of the propellant in the center of the chamber is, therefore, more profitable to improve the performance of the interior ballistics.

INTRODUCTION

The improvement factors for the gun performance are a design of propellant configuration, an ammunition design, a new propellant development, and an igniter modeling etc. The experiment studies have been limited for the phenomena of the large thrust in extremely short time intervals. For the study of these, therefore, it is necessary of a numerical code for the two-phase flow of the interior ballistics.

Numerical studies for the interior ballistics have been conducted in sequence of the lumped parameter model, one-dimensional two-phase model, and multi-dimensional two-phase model. Otto et al [1] have used the lumped parameter model for the prediction of the muzzle flash. The simple but very useful lumped parameter model has been used to analyze overall performance of cannons and to design grain geometry. The study on the ignition inducing pressure waves is clearly beyond the physical scope of this model.
Kuo et al [2] have completed the two-phase fluid dynamic method. The two-phase fluid mechanics approach has formulated the governing equations on the basis that mass, momentum, and energy fluxes are balanced over control volumes occupied separately by the gas and particle phases. These equations have used the Eulerian-Eulerian approach. Gough et al [3] have formed XKTC code by using the formal averaging method on the microscopic conservation equations for a single solid particle and the fluid. This formal averaging method has been extended to the multi-dimensional two-phase model, that is, NGEN code. The one-dimensional or multi-dimensional two-phase model has been used for the study of the ignition or the initial distribution of the propellants in the chamber. Nusca et al [4] have studied the progress of the simulated ignition in a solid propellant charge for the telescoped ammunition using NGEN code. Their study has demonstrated the value of the hierarchy of interior ballistic codes: An excellent agreement has been shown in prediction of maximum pressures using all three codes (IBHVG2, XKTC and NGEN3); A good agreement has been shown in the nature of pressure-wave simulations provided by XKTC and NGEN3; NGEN3 provided detailed insight into the controlling processes and interactions. Horst et al [5] have simulated a generic gun/propelling charge configuration using a range of interior ballistic models. XKTC and NGEN predicted temporary pressure-waves with the base pressure bigger than the breech pressure.

The case of Japan, Two-dimensional axisymmetric analysis code of interior ballistics has been developed by Hiroaki Miura at al [6]. Performance analysis of interior ballistics according to the combustion condition or propellant has been investigated using this code.

In Australia, R.J. Gollan[7] has developed the two-dimensional axisymmetric analysis code of interior ballistics using the AUSMDV method and the predictor-corrector method.

Recently, the domestic interior ballistics code (IBcode) for the two-phase flow has been developed [8]. A base of the study on the phenomena of interior ballistics in terms of ignition, flames spreading, and attendant pressure-wave formation as well as overall performance, has been accomplished.

For large guns, the propellant charge is usually contained in a metallic or combustible cartridge case affixed to the projectile; however, the propellant often does not fill all the available volume within the chamber [9]. In this situation, the position of the solid propellant in the chamber has a strong influence on performance of the interior ballistics. So, in this study, a performance of the interior ballistics according to the position of the solid propellant in the chamber has been investigated using the IBcode.

INTERIOR BALLISTICS

Interior Ballistics

![Figure 1. Actual Figure of the Cannon.](image)
Figure 1 shows the actual figure of a cannon chamber. As shown in Fig. 1 the propellant particles are filled in the chamber. The phenomena of the interior ballistics can be described like Fig. 2.

The interior ballistics can be divided into following processes 1-5.

1. Ignition of solid propellants with ignition gas
2. Increase of chamber pressure while burning solid propellants generate gases
3. Propellant particles moving by chamber pressure
4. Acceleration of the projectile
5. Escape of the projectile form the muzzle

Since the physical phenomena of the interior ballistics are very complicated, it is necessary of a numerical code for the analysis of the multi-dimensional two-phase flow.

**Governing Equation of Two Phase Flow**

The two-phase flow of the interior ballistics is composed of continuous phase of combustion gas and dispersal phase of solid propellants. Generally, the gas phase is calculated in Eulerian-coordinate system. The granular solid propellant particles are moving along the internal flow. Therefore the solid phase has been calculated by using the Lagrangian-coordinate systems.

In gas phase, the continuity, momentum and energy equations for one dimensional, compressible and unsteady flow are written in conservative forms as follows:

**Continuity equation,**

\[
\frac{\delta (\alpha \rho)}{\delta t} + \frac{\delta}{\delta x} (\alpha \rho u) = \dot{m} + \dot{m}_{\text{ign}}
\]  

(1)

**Momentum equation,**

\[
\frac{\delta (\alpha \rho u)}{\delta t} + \frac{\delta}{\delta x} (\alpha \rho uu) = -a \frac{\delta p}{\delta x} + \dot{m}_u - f
\]  

(2)
Energy equation,

$$\frac{\delta (\alpha E)}{\delta t} + \frac{\delta}{\delta x} (\alpha uE) = -\frac{\delta (\alpha pu)}{\delta x} - q_p - fu_p$$

$$+ m \left( \frac{e}{\rho_p} + \frac{p}{\rho_p} + \frac{u_p^2}{2} \right) + m \dot{e}_g$$

(3)

Porosity ($\alpha$) has been introduced to indicate that the proportion of solid phase. The subscript $p$ and $ig$ denotes the solid phase and the ignition gas, respectively.

The interaction between fluid and particles generally includes gravity, drag, and lift forces. Since the gravity and lift force are negligible because these are not the main factors for the motion of solid propellants, the motion of solid propellants considering only the drag force follows:

$$\frac{Du}{Dt} = \frac{1}{\rho_p} \left( \frac{150 \mu (1 - \alpha)}{\alpha d_p^2} + 1.75 \rho \frac{u - u_p}{d_p} \right) \times (u - u_p)$$

(4)

Equation (4) is called the Ergun’s [10] empirical equation. Where $\mu$ denotes the pore fluid viscosity, $d_p$ is the diameter of the solid propellant particles.

**Burning Surface Calculation**

The sliver should be considered in order to calculate of burning surface of 7-perforated propellant. There are two types of slivers, inner and outer. An inner sliver is any region of cross-section bounded by a triangle with the center of a perforation at each vertex. An outer sliver is any region of cross-section bounded by an arc of the grain's outer surface. According to number of the slivers, the burning processes are divided by 3 steps as shown in Fig. 3 (Step1: No sliver, Step2: 6 inner slivers and 6 outer slivers, Step 3: 6 outer slivers) [11].

![Figure 3. Configuration of 7-Perforated Propellant and Burning Steps](image-url)
Transmission and Loss of Interior Ballistics Energy

Solid propellant energy is divided into the translational kinetic energy of the projectile motion, the translational rotation energy of the projectile, the work done against the barrel friction, and the heat loss. In this research, the translational kinetic energy of the projectile motion and the work done against the barrel friction are only considered. The translation kinetic energy of the projectile motion is written as follows [12].

$$E_{proj} = \frac{1}{2}m_pV^2_{proj}$$

(10)

The work done against the barrel friction is calculated by pressure. It is written as follows [12].

$$E_{fric} = Area \times \int P_{res}(x)dx$$

(11)

Projectile Motion Equation

The projectile motion equations of all interior ballistics codes are similar each other. The force equilibrium equation of the projectile in the interior ballistics is

$$m_pA_p = (P_B - P_F)A_p - F_F - F_{drag}$$

(12)

The projectile motion equations are

$$\frac{dV_p}{dt} = a_p$$

(13)

$$\frac{dX_p}{dt} = V_p$$

(14)

NUMERICAL ANALYSIS

Numerical Method

The CFD code using 1-D finite volume method has been developed for the numerical study of the interior ballistics. The SIMPLE (Semi-Implicit Method for Pressure-Linked) algorithm and SMART [13] (Sharp and Monotonic Algorithm for Realistic Transport) scheme have been used to analyze the unsteady compressible flow. Also the ghost cell extrapolation method [14] has been used to analyze the moving boundary with the projectile movement.
Analysis Condition

In previous researches, the propellants have been assumed to be evenly distributed in the chamber. In this study, however, three cases of the existence of empty space in the chamber at which the propellants are not evenly distributed have been considered; propellants are located in the region near the base, propellants in the region near the breech, and propellant in the center of the chamber, respectively. Fig. 4 shows the diagram of the cases; previous modeling: uniformly distributed, case 1: locally distributed to the breech, case 2: locally distributed to the center, case 3: locally distributed to the base.

Initial Condition

Table 1 shows the initial condition of numerical analysis of the interior ballistics. Same amount of the propellant is used in each case and the central ignition along the length of the charge is assumed regardless of the propellant distributions.

<table>
<thead>
<tr>
<th>TABLE I : INITIAL CONDITION</th>
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<tbody>
<tr>
<td>Projectile Mass</td>
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<tr>
<td>Propellant Mass</td>
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<tr>
<td>Propellant Density</td>
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<tr>
<td>Propellant Impetus</td>
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<tr>
<td>Igniter Mass</td>
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<td>Igniter Impetus</td>
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<tr>
<td>Chamber Volume</td>
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<tr>
<td>Caliber</td>
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<tr>
<td>Barrel Length</td>
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</table>
Verification

IBHVG2 used widely in previous studies has been applied to verify the IBcode. Figure 5 shows the mean pressure of the previous analysis case for each of IBcode and IBHVG2. The analysis results of the two codes are similar in mean pressure as a function of time. The results show the error of 2% or less. Therefore, reliability of the IBcode has been obtained.

Results

Figure 6(a) shows the breech pressure according to propellant position in the chamber. The case of the propellant located in the region near the breech, the chamber pressure increases locally. In other words, the pressure of the region near the breech increases fast. Then the pressure wave is created and propagates to the empty space (base). Contrarily, the case of the propellant located in the region near the base, the pressure of the near base increases fast. In this case, pressure wave propagates to the empty space (breech). Because of these phenomena, the pressure oscillations appear. But, the case of the propellant located in the center of the chamber, the chamber pressure increases uniformly. Then the pressure wave is not created and the pressure oscillations do not appear, too.

In case of the propellant located in the region near the breech, the pressure near the breech increases and propagates to the base. Therefore, elevated pressure hits the projectile and strong pressure wave is reflected to the breech. For this reason, pressure of the breech case is particularly higher than other cases. Moreover, in this case, breech pressure rises immediately. But, in other cases, it takes more time until the pressure wave propagates to the breech. So that, time delay occurs.

Figure 6(b) shows the base pressure according to the propellant position in the chamber. For the same reason, the pressure oscillations appear in the cases of the propellant used in regions near the breech and the base. The pressure oscillations do not appear in the case of the propellant used in the region near the center of the chamber.
In case of the propellant located in the region near the base, the pressure near the base increases fast. So, projectile moves faster than other cases. For this reason, the mean pressure of the chamber decreases and intensity of the pressure wave decreases too. Because of this, extraordinary rise in pressure does not occur unlike the Fig. 6. Also, in this case, base pressure rises immediately. But, in other cases, time delay occurs until the base pressure rises too.

Figure 7(a) reveals the pressure contour of the breech case on the distance-time plane. As mentioned above, a rapid pressure rise can be found on the region near the breech. Because of this, the pressure wave is generated and propagates to the base region. The pressure oscillations caused by pressure waves are, therefore, observed. And the highest pressure in case of the analysis is observed.

Figure 7(b) denotes the pressure contour of the center case on the distance-time plane. Unlike the breech case, pressure oscillations are not observed. A pressure rise occurs in the middle of chamber and the pressure wave propagates evenly to both sides (breech and base). Therefore, the internal flow is very stable.

Figure 7(c) shows the pressure contour of the base case on the distance-time plane. As mentioned above, a rapid pressure rise can be found on the region near the base. In contrast to the breech case, the pressure wave is generated and propagates to the breech region. Similar to the breech case, the pressure oscillations caused by pressure wave are observed too.
Figure 8(a) reveals the differential pressure according to the propellant position in chamber. The differential pressure means the pressure difference between the breech and the base. The quantity indicated on the differential pressure profile as $-\Delta P$, known as the initial reverse differential pressure, can be negative affect to the performance of the interior ballistics.

The cases of the propellant located in the region near the base and the breech have shown that the negative differential pressure and the pressure difference between the breech and the base are much higher than those of the case of the propellant located in the center of the chamber. The case of the propellant in the center of the chamber is, therefore, more profitable to improve the performance of the interior ballistics.

Figure 8(b) shows the acceleration versus the travel distance of projectile for each propellant position in chamber. In recent years, the controller is mounted on the projectile for a gliding or a precision strike, unlike the conventional projectile. So, large acceleration could have a negative effect on the controller of the projectile. In terms of the stability of the projectile, the center-positioned propellant in the chamber is beneficial to improve the performance of the interior ballistics too.

CONCLUSION

The numerical analysis on the characteristics of the interior ballistics according to the solid propellant positions in the chamber has been conducted. For this study, three cases of analysis have been considered. As the results, the cases of the propellants located in the region near the base and the breech have shown that the negative differential pressure and the pressure difference between the breech and the base are much higher than those of the case of the propellant located in the center of the chamber. Since the negative differential pressure and the rapid gradient of pressure in the chamber have a negative impact on the cannon performance, the case of the propellant in the center of the chamber is, therefore, more profitable to improve the performance of the interior ballistics. Additional research for the precise study on the stability and the performance of the cannon is, however, needed such as igniter injection etc.

ACKNOWLEDGMENTS
REFERENCES