

## MODELING AND SIMULATION OF THE GAS CHARGING AND DISCHARGING PROCESSES ON GUN BORE EVACUATOR

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The mathematical models for getting the analytical solutions of gas charging and discharging processes of gun bore evacuator were formulated based on thermodynamics and gas equation of state. Three-dimensional transient CFD simulations were conducted to study the detailed flow behaviour during the gas charging and discharging processes of the bore evacuator. Based on the mathematical models and the CFD simulation results, a calculation code for evaluating the bore evacuator performance was developed to aid the bore evacuator design and thus to improve the efficiency of the bore evacuator.

### INTRODUCTION

The gun bore evacuator is a pressure vessel surrounding a portion of the gun tube. During firing, a small part of high pressure propellant gases is charged and stored in the bore evacuator. After the projectile exits the muzzle, the high pressure gases in the bore evacuator discharge towards the muzzle end. The forward flow induces and purges the remaining propellant gases at the breech end.

The performance of bore evacuator is closely related to the gas charging and discharging processes. The efficiency of bore evacuator can be defined by the amount of induced mass flow at breech end and the flow duration time. An indicator, mass flow augmentation ratio, is also used to determine the efficiency of bore evacuator. It is the ratio of induced mass flow from the breech to the ejected mass flow through the discharge holes of bore evacuator.

From the literature survey, it is found that a lot of works have been done on the experimental measurements of bore evacuator [1~4]. Besides, the bore evacuator flow theory and the CFD simulation was also studied by some authors [5~8]. However, there is still the need for more detailed research and more systematic approach to optimize bore evacuator design.

## MATHEMATICAL MODELING

In order to analyze the performance of the bore evacuator, it is necessary to make the mathematical modeling of gas charging and discharging processes. The formulated mathematical model should be simple so that the analysis can be done within short time with a personal computer. This would be practical for engineers to perform the analysis and evaluate the effectiveness of the bore evacuators of different designs, so that the optimum design is established quickly. The mathematical models derived by the authors based on thermodynamics and gas equation of state are as follows.

### Mathematical Model of Gas Charging Process

For the process of gas charging into the bore evacuator during firing, the gas pressure in the evacuator increases and the calculation model is:

$$P_c = P_{c0} + \frac{A_c k}{V_c} K_0 \sqrt{\frac{P_{s0}^{1/k}}{\rho_{s0}}} \int_0^t P_s^{\frac{3k-1}{2k}} dt \quad (1)$$

where  $P_c$  is the pressure in bore evacuator during charging,  $P_{c0}$  is the pressure in bore evacuator before charging,  $V_c$  is the volume of bore evacuator,  $A_c$  is the total area of charge holes,  $P_{s0}$  and  $\rho_{s0}$  are the initial pressure and density of chamber gas before charging,  $P_s$  is the chamber pressure during charging,  $t$  is the charging time,  $k$  is the ratio of gas specific heat ( $C_p/C_v$ ),  $K_0 = \left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}} \sqrt{k}$ .

### Mathematical Model of Gas Discharging Process

For the process of gas discharging from the bore evacuator to the gun tube after firing, the gas pressure in the evacuator slowly decreases and the calculation model is:

$$P_d = P_{d0} (1 + B_d t)^{\frac{2k}{1-k}} \quad (2)$$

where  $P_d$  is the pressure in bore evacuator during discharging,  $P_{d0}$  and  $\rho_{d0}$  are the initial discharging pressure and density of gas in bore evacuator,  $V_d$  is the volume of bore evacuator,  $A_d$  is the total area of discharge holes,  $B_d = \frac{A_d K_0 (k-1)}{2V_d} \sqrt{\frac{P_{d0}}{\rho_{d0}}}$ .

The gas discharging time of bore evacuator is:

$$t = \frac{1}{B_d} \left( \left( \frac{P_{d0}}{P_d} \right)^{\frac{k-1}{2k}} - 1 \right) \quad (3)$$

The total discharged mass flow of bore evacuator is:

$$M = S_d K_0 \sqrt{P_{d0} \rho_{d0}} \int_0^t (1 + B_d t)^{\frac{1+k}{1-k}} dt \quad (4)$$

where  $\rho_{d0}$  is the initial gas density in bore evacuator.

## CFD SIMULATION

The mathematical models formulated above were based on thermodynamics and gas equation of state. Another way to formulate the mathematical models of the gas charging and discharging processes is based on the conservation's equations such as the conservation of mass, momentum and energy. The difference between those two kind of models is that the direct analytical solution can be obtained for the former, while an numerical method such as the Finite Difference Method or the Control Volume Method has to be used for the later. The numerical solution of the conservation's equations is the well-known CFD simulation. As CFD simulation provides detailed information such as pressure, velocity and temperature fields during the whole dynamic process, it is more computing intensive than the analytical solution thus a high performance computer is needed.

Although 2D and 3D steady state CFD simulations of bore evacuator were made by some researchers [6,7,8], 3D transient CFD simulation has not been reported. As the gas charging and discharging processes of the bore evacuator are time dependent process, the transient CFD simulation has to be used to obtain the time dependent information such as changing of pressure and mass flow rate with time in the bore evacuator and in the gun tube. Besides, 3D simulation is necessary to accurately determine the mass flux induced at the breech end due to the jet entrainment near the discharge holes of bore evacuator.

## Simulation Conditions

The 3D transient CFD simulations of the high-speed and compressible flow in bore evacuator were carried out by the authors with the commercial code FLUENT5. The gas charging and discharging processes were simulated separately. The result from simulated charging process is used as the initial condition for discharging process.

In addition, we used the CFD method to perform sensitivity study on some parameters that could not be included in the mathematical models derived. The following parameters were investigated to see their effects on the gas charging and discharging processes of bore evacuator:

- Charge hole angle
- Charge hole number
- Charge hole position
- Discharge hole angle
- Discharge hole number
- Discharge hole position
- Gun tube length
- Initial discharge pressure

For each parameter, at least three simulation cases were run with different value of the parameter. Thus more than 24 simulation cases were run and the run time on each case being about 2 ~ 3 days using a SGI Origin 2000 workstation.

## **Simulation Results**

The simulated velocity field in the bore evacuator during charging is shown in Figure 1. It can be seen that the velocity distribution during charging depends on the location of charge holes. The highest velocity is about 650 m/s, which is in the region of the charge holes.

The simulated velocity field in the bore evacuator and gun tube during discharging is shown in Figure 2. The result indicates that the gas velocity in the bore evacuator is very low during discharging process, but the gas velocity at the discharge nozzles is very high which forms the gas jets in the tube. These gas jets induce the flow in the gun tube, which removes the fume through muzzle end.

The pressure characteristic in the bore evacuator during charging is shown in Figure 3 and Figure 4. From Figure 3, it can be seen that the charge hole angle has greater influence on the final charged pressure in the evacuator. The smaller the charge hole angle, the lower the charged pressure. The reason is that the wall of charge hole with smaller angle has higher resistance to the high velocity charging gas, so the final charged pressure in the evacuator becomes lower. From Figure 4, it can be seen that maintaining total charge hole area, the number of charge holes has little influence on the final charged pressure in the evacuator.

Figure 5 shows the simulated mass flow rate at both the discharge nozzles and the breech end during discharging process. It is evident that the small mass flow at discharge nozzles can induce big mass flow at the breech end. In this case, the induced mass flow rate at breech end is about 7~10 times of the mass flow rate at discharge nozzles.

Figure 6 presents a comparison of the simulated mass flow augmentation ratio with the experimental one [4], which gives good agreement.

During discharging process, the influence of the discharge nozzle angle on the induced mass flow at the breech end is shown in Figure 7. It can be seen that the nozzle slant angle has significant influence on the induced mass flow rate. The smaller the nozzle slant angle, the higher the induced mass flow rate. This is because the induced mass flow rate depends mainly on the nozzle velocity component along the tube axis.

The influence of the number of discharge nozzles on the induced mass flow at the breech end is shown in Figure 8. It can be seen that with the total nozzle area maintaining constant, the number of discharge nozzles has little influence on the induced mass flow at the breech end.

The influence of gun tube length on the induced mass flow rate at the breech end is shown in Figure 9. It can be seen that the shorter the gun tube, the bigger the induced mass flow. This is due to the smaller flow resistance with the shorter gun tube.

The influence of discharge nozzle position on the induced mass flow at the breech end is shown in Figure 10. From the simulated result of the three locations it can be seen that the closer the nozzle to the breech, the bigger the induced mass flow.

## DESIGN CODE DEVELOPMENT

Designing an efficient bore evacuator is very important to a gun system. However, the mathematical model based on thermodynamics and gas equation of state is not good enough to evaluate the efficiency of bore evacuator because some parameters could not be included in the model. Although the CFD model is good enough to aid the bore evacuator design, the CFD simulation is very time consuming and needs the corresponding software and hardware. Thus, a fast and efficient design code is expected to aid the bore evacuator design.

Therefore, we combined the CFD simulation results with the mathematical models and developed a design code called BECAD to calculate the efficiency of the bore evacuator and speed up the bore evacuator design. The inputs for the calculation code are the configuration and position of the bore evacuator, the areas and position of charge and discharge holes, the internal ballistics data. The outputs include the peak pressure of the bore evacuator after charging, the charged mass amount, the discharge time and the discharge mass amount.

The flow chart of the BECAD code is shown in Figure 11.

## CONCLUSIONS

The mathematical models based on thermodynamics and gas equation of state were formulated for the gas charging and discharging processes of bore evacuator. Although these models were simple and easy for analytical solutions, they were not satisfactory due to the limitation of the models. The 3D transient CFD simulation was applied to study the detailed gas flow behaviour in the bore evacuator. In addition, the sensitivity of the geometry parameters was obtained from the CFD simulations. By combining the mathematical models with the CFD simulation results, a calculation code was developed to evaluate the efficiency of bore evacuator. This code has been used to improve the design of the bore evacuator.

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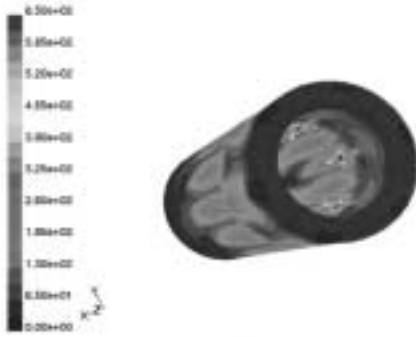


Figure 1. Simulated velocity distribution in bore evacuator during charging.

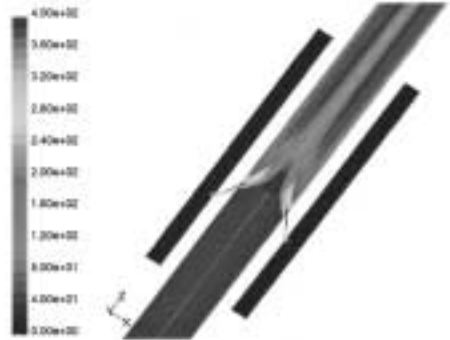


Figure 2. Simulated velocity distribution in bore evacuator and gun tube during discharging.

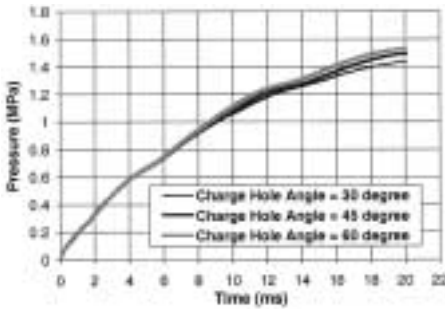


Figure 3. Influence of charge hole angle on the charged pressure on bore evacuator.

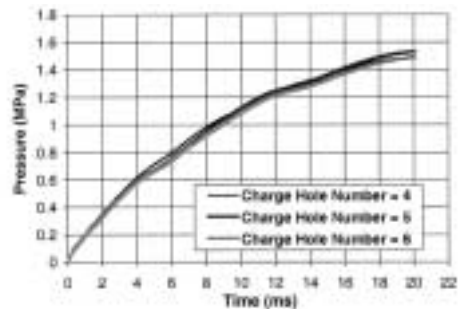


Figure 4. Influence of the number of charge holes on the charged pressure in bore evacuator.

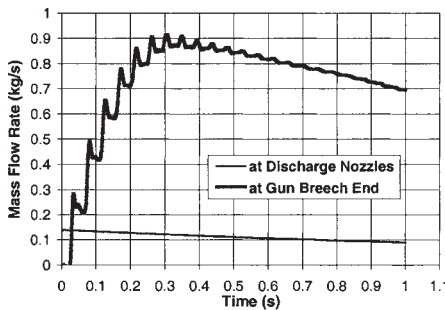


Figure 5. The discharged and the induced mass flow rates during discharging.

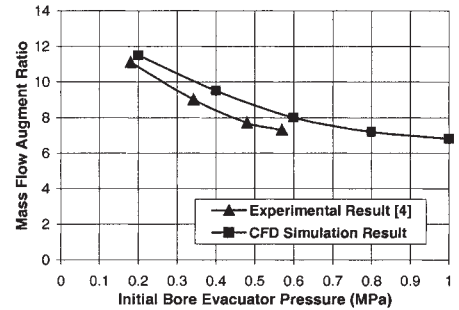


Figure 6. Comparison of measured and simulated mass flow augmentation ratio during discharging.

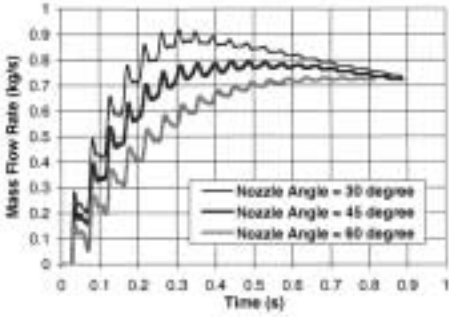


Figure 7. Influence of the discharge nozzle angle on the induced mass flow at gun breech.

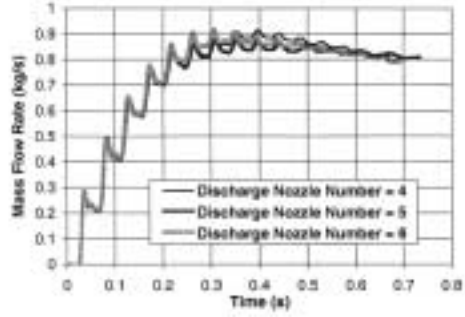


Figure 8. Influence of the number of discharge nozzles on the induced mass flow at gun breech.

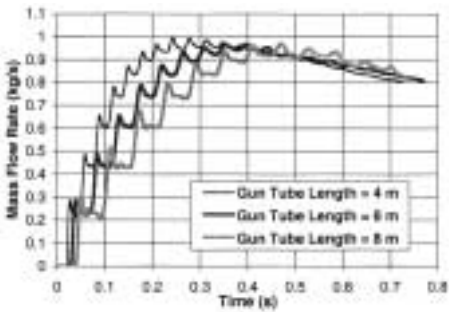


Figure 9. Influence of the gun tube length on the induced mass flow at gun breech.

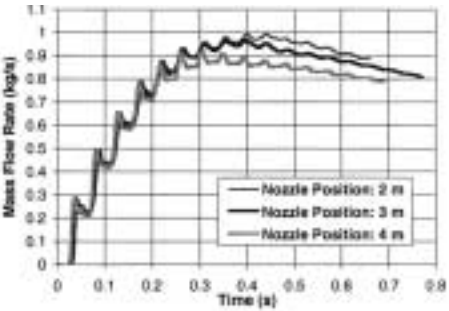


Figure 10. Influence of the discharge nozzle position on the induced mass flow at gun breech.

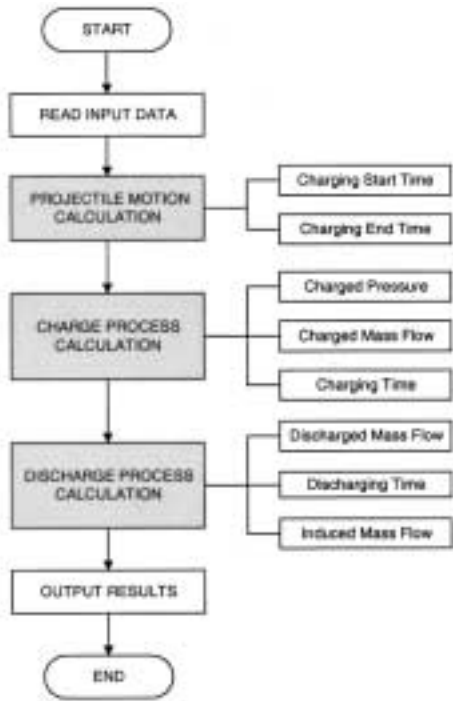


Figure 11. Flow chart of the BECAD code.