# Study on the influence of air in the recoil mechanism on artillery performance during firing

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## ABSTRACT

*This paper investigates the influence of air and structural parameters of the hydraulic recoil mechanisms on the firing process and stability of artillery systems. A mathematical model is developed to describe the internal firing process of the artillery and the dynamics of the recoil components during both the recoil and counter-recoil phases. The paper also calculates the influence of air in the recoil mechanism on recoil resistance force, recoil velocity, recoil displacement, and force distribution characteristics by incorporating the compressibility of the fluid-air mixture through the effective bulk elastic modulus. The paper also investigates the influence of the initial working chamber volume of the recoil brake mechanism on the movement of the recoil components. Simulation results with the artillery D-44 85 mm show that neglecting the influence of air leads to a higher and earlier peak recoil resistance force, a shorter and less stable force stabilization zone, and therefore can cause adverse force impulses acting on the artillery structure. The research results provide a valuable theoretical basis for evaluating the working efficiency of the recoil braking mechanism, as well as contributing to improving the reliability, durability, and technical maintenance efficiency of ground artillery systems.*

**Keywords:** Hydraulic recoil mechanism; Air; Recoil stability; Artillery dynamics; Numerical simulation.

## 1. INTRODUCTION

Modern artillery systems are equipped with elastic mountings and hydraulic recoil mechanisms to control the recoil motion generated during firing. The recoil mechanism is essential for absorbing and dissipating the kinetic energy of the recoiling mass, thereby ensuring firing stability, accuracy, and structural durability. Its reliable operation is therefore a decisive factor in modern artillery design.

In practice, the hydraulic recoil braking mechanism operates on the throttling principle, converting recoil kinetic energy into heat through viscous losses of the working fluid. However, real operating conditions are affected by non-ideal phenomena such as cavitation, air entrainment, fluid compressibility, and pressure fluctuations. Previous numerical and experimental studies have shown that cavitation and air presence can significantly alter pressure distribution, braking force characteristics, and overall recoil performance, potentially reducing system reliability and durability [1-3].

Accurate modeling of recoil and counter-recoil dynamics is necessary to predict recoil displacement, velocity, and force characteristics. Numerical studies have demonstrated that recoil behavior can only be reliably evaluated through coupled dynamic equations solved with sufficient numerical accuracy [4]. Furthermore, structural parameters and clearances within the recoil mechanism strongly influence hydraulic resistance, energy dissipation, and recoil stability [5-7].

From a theoretical standpoint, the analysis of artillery recoil systems is based on classical artillery design theory and internal ballistics [8], together with well-established hydraulic and fluid power control theories [9, 10]. In hydraulic systems, it is widely recognized that entrained air reduces the effective bulk modulus of the working fluid, thereby affecting pressure response, damping force, and system stability [11]. Classical dynamics theory provides the fundamental framework for analyzing such time-varying mechanical systems [12-14].

Despite extensive research, most existing studies focus on individual aspects of recoil behavior, such as hydraulic flow, cavitation, or recoil dynamics, without fully considering their coupled effects. In particular, the combined influence of air entrainment and key structural parameters of the hydraulic recoil braking mechanism on firing stability has not been sufficiently investigated for practical field artillery systems.

In this paper, a coupled numerical model is developed to analyze the internal ballistic process and recoil-counter-recoil dynamics of an artillery system. The effect of air entrainment is incorporated through the effective compressibility of the hydraulic fluid, and the influence of key structural parameters, including the initial working chamber volume, is systematically investigated.

## 2. PROBLEM

### 2.1. Research methods

This study investigates the influence of air entrainment in the recoil mechanism on the operational performance of artillery by combining theoretical analysis and numerical simulation.

First, the internal ballistic process of the cannon is modeled to determine the propellant gas pressure and recoil force acting on the barrel during firing. The governing differential equations describing projectile motion and gas pressure evolution are solved numerically using the fourth-order Runge - Kutta method. The obtained recoil force serves as the input parameters for the recoil mechanism model.

Second, a dynamic model of the recoil mechanism is established, considering the interaction between the recoiling mass, the hydraulic recoil brake, and the pneumatic recuperator. The recoil motion is described by the equation of motion of the recoiling mass, which includes the propellant gas force, hydraulic damping force, pneumatic restoring force, and frictional resistance. The hydraulic braking force is derived from fluid flow theory, taking into account throttling effects through variable orifices.

To evaluate the influence of air within the recoil mechanism, the compressibility of the hydraulic fluid-air mixture is incorporated into the model. The presence of air is represented by modifying the effective bulk modulus of the working fluid, which directly affects pressure variation, damping force, and recoil stability.

Finally, the coupled system of differential equations governing internal ballistics and recoil motion is solved numerically using MATLAB. A parametric study is conducted to assess the sensitivity of recoil characteristics to air presence, thereby providing a scientific basis for evaluating recoil mechanism performance and improving operational reliability.

### 2.2. Formulations

#### *2.2.1. Solution of the internal ballistics problem of the artillery gun*

To simplify the computational process, within the scope of this study, the following basic assumptions are adopted:

- The propellant burns according to a geometric burning law $u = u_1 p$, and the propellant combustion behavior is described by the corresponding mathematical formulation (linear burning law).

- All secondary work components of the propellant gases are proportional to the primary work responsible for the translational motion of the projectile and are accounted for by the secondary work coefficient $\varphi$.

- The entire propellant charge is assumed to burn under uniform pressure conditions equal to the internal ballistic pressure.

- The composition of the combustion products is assumed to remain constant; consequently, the parameters *f* and *α* are also considered invariant.

- At the moment when the propellant gas pressure reaches the projectile start pressure $p_0$, the driving band is assumed to be instantaneously engraved, and the projectile begins its motion.

The system of equations governing the internal ballistics is expressed in the following form:

$$\begin{cases} 1.\dfrac{dv}{dt}=\dfrac{Sgp}{\varphi q};\quad 2.\dfrac{dl}{dt}=v;\quad 3.\dfrac{dz}{dt}=\xi_1\dfrac{p}{I_k}; \\ 4.\dfrac{d\psi}{dt}=\xi_1\chi\left(1+2\lambda z+3\mu z^2\right)\dfrac{p}{I_k};\quad 5.\,p=\dfrac{f\omega\psi-\dfrac{\theta\varphi q v^2}{2g}}{W_0-\dfrac{\omega}{\delta}(1-\psi)-\alpha\omega\psi+Sl} \end{cases} \tag{1}$$

In this study, a numerical approach employing the Runge-Kutta algorithm is used to solve the internal ballistics problem. The initial conditions for the solution, defined from the instant when the driving band begins to be engraved, are:

$$v_0=0;\quad l_0=0;\quad t_0=0;\quad p=p_0;\quad z=z_0;\quad \psi=\psi_0\,.$$

*2.2.2. Solution of the inverse recoil problem of the artillery gun*

The objective of this recoil inverse problem is, based on the known specific structural configuration of the gun's recoil brake mechanism, to determine the recoil parameters such as the recoil resisting force *R*, recoil velocity *V*, and recoil displacement *λ*. These parameters are then used to evaluate and analyze the operating process of the recoil braking device, thereby providing supplementary insights to the theoretical framework.

The system of differential equations governing the motion of the recoiling mass is expressed as follows:

$$\frac{dV}{dt}=\frac{P_{\lg}-R}{M_o};\qquad \frac{dX}{dt}=V \tag{2}$$

where $P_{\lg}$ is the resultant propellant gas force acting on the bore, *R* is the resultant recoil resisting force, which is determined according to the following formula:

$$R = \Phi_L + \Pi + R_f - Q_0\sin\varphi \tag{3}$$

where ΦL is the hydraulic braking force, Π is the counter-recoil force; $R_f$ is the resultant friction force; weight of the recoiling mass.

The counter-recoil force is determined by the following formula:

$$\Pi=\Pi_0\left(\frac{S_o}{S_0-X}\right)^k \tag{4}$$

The resultant friction force is determined by the following formula:

$$R_f = fQ_0\cos\varphi_{gh}+\gamma Q_0 \tag{5}$$

The hydraulic recoil braking force is determined by the following formula:

$$\Phi_L = p_1(A_1-A_V)+k_3\frac{\rho}{2}\frac{A_{hd}^3}{\Omega^2}V^2 \tag{6}$$

In calculating the recoil motion, it is common to base the analysis on the law governing the resultant propellant gas force $P_{\mathrm{lg}}$. For the purpose of more conveniently investigating the recoil phenomenon, the entire recoil process over time is conventionally divided into three stages:

*Stage I: the period during which the projectile moves inside the barrel:

$$P_{\mathrm{lg}} = pS \tag{7}$$

*Stage II: the period of the final action of the propellant gases:

$$P_{\mathrm{lg}} = \chi p_d S \,\mathrm{e}^{-\frac{t}{b}} \tag{8}$$

*Stage III: the period during which the recoiling mass moves by inertia:

$$P_{\mathrm{lg}} = 0 \tag{9}$$

## 3. RESULTS AND DISCUSSION

### 3.1. Input data

To carry out the investigation, the research object employed is the Russian 85-mm long-barrel D-44 gun, with the internal ballistic parameters and structural parameters specified below:

The parameters used for the internal ballistics calculations are presented in Table 1.

***Table 1.*** *Basic internal ballistic parameters of the 85-mm D-44 gun.*

| No. | Basic parameters | Symbol | Value | Unit |
|---|---|---|---|---|
| 1 | Caliber | $D$ | 0.85 | dm |
| 2 | Initial combustion chamber volume | $W_{\mathrm{cb}}$ | 3.94 | dm$^3$ |
| 3 | Cross-sectional area of the bore | $S$ | 0.582 | dm$^2$ |
| 4 | Barrel length | $l_{\mathrm{d}}$ | 35.92 | dm |
| 5 | Projectile weight | $q$ | 9.54 | kG |
| 6 | Projectile driving pressure | $p_0$ | 3.10$^4$ | kG/dm$^2$ |
| 7 | Propellant mass | $\omega$ | 2.48 | kG |
| 8 | Propellant force | $f$ | 980000 | kG.dm/kG |
| 9 | Covolume | $\alpha$ | 1 | dm$^3$/kG |
| 10 | Propellant density | $\delta$ | 1.6 | kG/dm$^3$ |
| 11 | Total pressure impulse | $I_{\mathrm{k}}$ | 1270 | kG.s/dm$^3$ |
| 12 | Adiabatic exponent | $k$ | 1.2 | |

Structural parameters of the recoil braking mechanism of the 85-mm D-44 gun are presented in Table 2.

***Table 2.*** *Structural parameters of the recoil braking mechanism of the 85-mm D-44 gun.*

| No. | Basic parameters | Symbol | Value | Unit |
|---|---|---|---|---|
| 1 | Regulating ring diameter | $d_{\mathrm{v}}$ | 38 | mm |
| 2 | Outer diameter of the piston | $D$ | 102 | mm |
| 3 | Inner diameter of the recoil rod | $d_l$ | 42 | mm |
| 4 | Outer diameter of the recoil rod | $d_{hl}$ | 48 | mm |
| 5 | Diameter of the oil flow orifice | $d_{lc}$ | 3.5 | mm |
| 6 | Piston diameter | $D_{dl}$ | 55 | mm |
| 7 | Piston rod diameter | $d_c$ | 22 | mm |
| 8 | Polytropic index of compressed gas | $n$ | 1.2 | |

| No. | Basic parameters | Symbol | Value | Unit |
|---|---|---|---|---|
| 9 | Recoil length | $\lambda$ | 580 ÷ 660 | mm |
| 10 | Maximum permissible recoil length | $\lambda_{gh}$ | 675 | mm |
| 11 | Mass of the recoiling parts | $M_0$ | 785 | kg |
| 12 | Muzzle brake form factor | $\alpha_{hl}$ | - 0.183 | |
| 13 | Friction coefficient of the guide rails | $f$ | 0.2 | |
| 14 | Proportional coefficient of the resultant friction force | $v$ | 0.3 | |

Regulating rod diameters corresponding to the recoil length are presented in Table 3.

***Table 3.*** *Regulating rod diameter corresponding to the recoil length.*

| $L$ (dm) | 0 | 0.23 | 0.556 | 1.06 | 1.4 | 1.68 | 2.01 | 2.43 |
|---|---|---|---|---|---|---|---|---|
| $\delta$(mm) | 35.5 | 30.4 | 30.1 | 31.65 | 32.43 | 32.9 | 33.35 | 33.9 |
| $L$ (dm) | 3.25 | 3.93 | 4.53 | 4.93 | 5.33 | 5.98 | 6.53 | 7.00 |
| $\delta$(mm) | 35.0 | 35.5 | 35.7 | 35.9 | 36.3 | 36.7 | 37.2 | 38 |

### 3.2. Results of solving the internal ballistics problem and the motion problem of the recoiling mass

The results of the internal ballistic analysis of the 85 mm D-44 gun are presented in Figures 1 and 2.

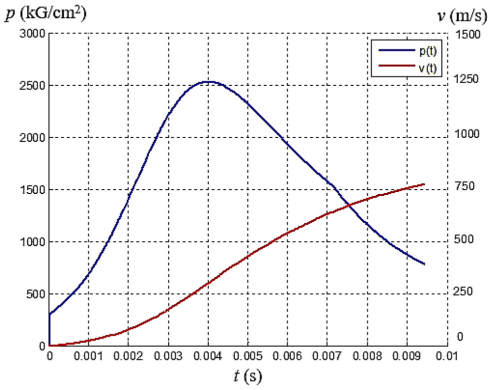

***Figure 1.*** *Pressure and velocity versus time.*

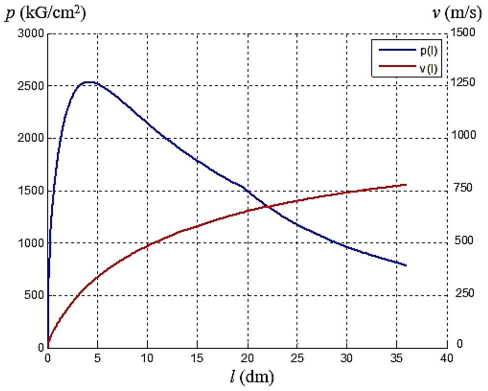

***Figure 2.*** *Pressure and velocity versus displacement.*

The internal ballistic calculation results are in good agreement with the experimental data and the values reported in [15].

- The calculated maximum pressure in the barrel is 2534.5 kG/cm², whereas the value given in [15] is 2550 kG/cm²; after unit conversion, the resulting error is 0.61%.

- The calculated muzzle velocity of the projectile is 775.32 m/s, compared with 793 m/s reported in Reference [4], corresponding to an error of 2.23%.

The observed discrepancies are mainly attributed to the simplifying assumptions introduced in the calculation process. Nevertheless, the overall computational accuracy is satisfactory, and the errors remain within acceptable limits.

The variations of the recoil resistance force and the recoil velocity with respect to the recoil displacement at the elevation angle $\varphi = 0°$ are illustrated in Figures 3 and 4.

It can be observed that the calculated recoil resistance force *R(t)*, obtained based on the actual structural configuration, shows good agreement with the idealized theoretical law.

The *V(X)* relationship is also reasonable. Initially, the recoil velocity *V(X)* increases rapidly, reaching its maximum value during the first phase when the projectile is moving inside the barrel, and then decreases gradually, ensuring smooth recoil of the gun.

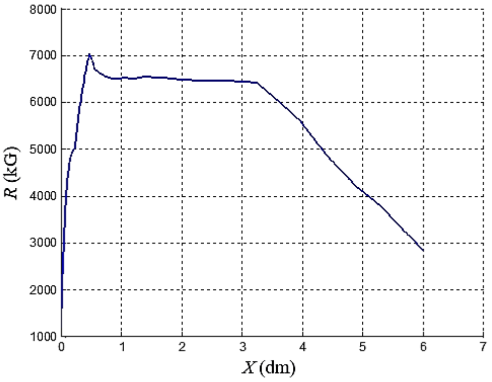

***Figure 3.** Recoil resistance force versus recoil displacement.*

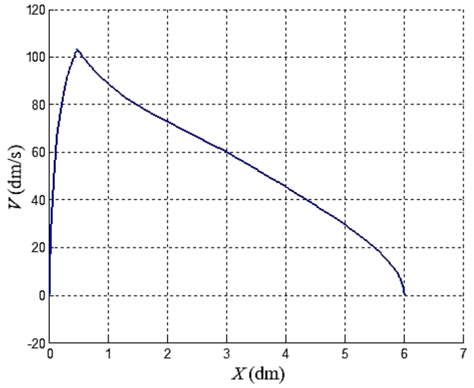

***Figure 4.** Recoil mass velocity versus recoil displacement.*

The recoil length of the gun is 6.0191 dm at an elevation angle of 0°. These values are reasonable and lie within the allowable range of the gun ($5.80 < X < 6.60$ dm).

### 3.3. Influence of air on the operation of the gun during firing

The solution of the inverse recoil problem without considering the effect of air and that including the effect of air differ only in the expression used to determine the hydraulic braking force $\Phi_L$. The obtained results are as follows:

When the effect of air is taken into account, the recoil resistance force characteristic exhibits three distinct stages: a rapid increase at the beginning of the stroke, a stable plateau over the middle portion, and a gradual decrease toward the end. The peak force reaches 66.38 kN, then remains approximately constant at 62 - 64 kN over most of the stroke, before decreasing smoothly near the end. This behavior indicates a well-distributed force profile, ensuring stable absorption of the recoil mass kinetic energy, while maintaining sufficient force at the end of the stroke to effectively damp out the motion.

When the effect of air is neglected, the force characteristic exhibits a markedly different behavior. The peak force reaches a higher value of approximately 67.05 kN and occurs very early at the beginning of the recoil stroke. After reaching the peak, the force decreases more rapidly, then stabilizes at a lower level of about 57 - 59 kN over the intermediate region, before dropping sharply toward the end of the stroke to approximately 25 kN. Thus, in the absence of air effects, the peak force is higher and appears earlier, while the “plateau” region is shorter and less stable.

The comparative results indicate that neglecting the effect of air in the recoil chamber leads to a higher and earlier peak recoil resistance force, followed by a rapid decay and a shortened stable region. This results in a non-uniform load distribution, which may induce unfavorable impulse loads on the gun assembly. In contrast, when the effect of air is considered, the force characteristic becomes smoother: the peak force is maintained at a reasonable level, the stable region is extended, and the force decreases gradually toward the end of the stroke, ensuring safe and effective damping of the recoil mass motion.

Both curves (with and without the effect of air) exhibit a typical behavior: the recoil velocity increases rapidly at the beginning of the stroke, reaches its maximum over a very short interval, and then decreases gradually until the recoil mass comes to a complete stop. The curves are continuous and smooth, without abnormal oscillations, indicating stable operation of the recoil system.

The comparative results show that the two velocity-displacement characteristics almost coincide, with only minor differences in the initial stage: the peak velocity in the case without air is slightly higher than that in the case considering air. Thus, accounting for the effect of air only slightly reduces the maximum recoil velocity, while the overall braking process remains essentially unchanged. Nevertheless, limiting the peak velocity is of practical importance, as it helps reduce the initial impulse and enhances the smoothness of the recoil system operation.

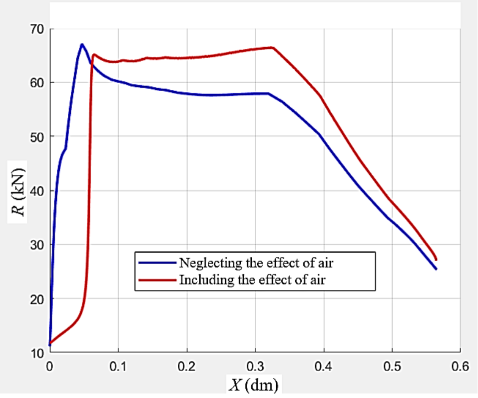

***Figure 5.*** *Recoil resistance force R(X) considering the effect of air.*

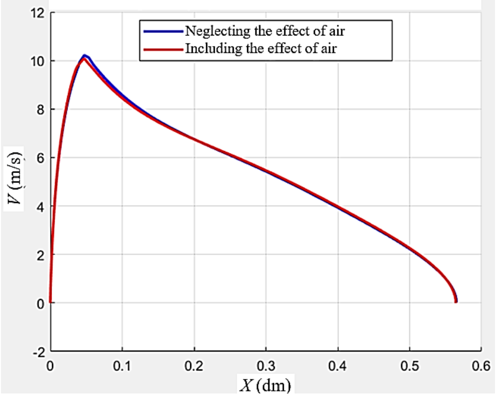

***Figure 6.*** *Recoil velocity V(X) considering the effect of air.*

### 3.4. Influence of the initial volume of the working chamber in the recoil braking mechanism on the operation of the gun during firing

In the recuperator-type recoil braking mechanism, the initial volume $W_0$ of the working chamber plays a decisive role in the compression characteristics of the medium and, consequently, has a direct influence on the generated pressure, the braking force, and the motion law of the recoil mass. Investigating different values of $W_0$ makes it possible to assess the sensitivity of the system to this parameter and to determine an appropriate range that ensures stable recoil resistance force, recoil mass velocity within safe limits, and pressure levels in the mechanism that do not exceed allowable values.

By solving the inverse recoil function problem while accounting for the effect of air, and investigating the influence of $W_0$ on the motion of the recoil mass, the results are presented in Figure 7.

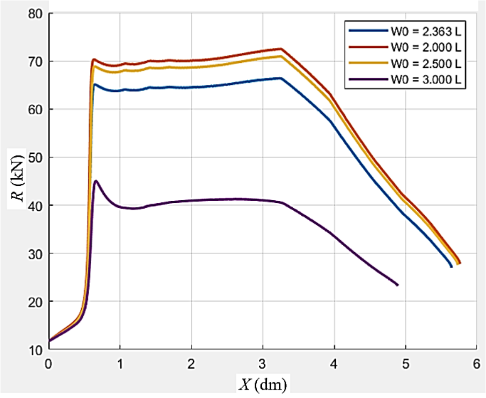

***Figure 7.*** *Recoil resistance force R(X) considering variations in the initial volume.*

The simulation results confirm that the initial volume $W_0$ has a decisive influence on the recoil braking process. For a small $W_0$ (2.0 L), the braking force reaches a high peak ($R \approx 72$ - 75 kN ), ensuring strong control of the recoil mass but potentially causing structural overload. When $W_0$ is increased to an appropriate range (2.3 - 2.5 L), the force and pressure remain within a stable range ($R \approx 65$ - 70 kN), the peak recoil velocity is about 10 - 11 m/s, and the braking process becomes safe and smooth. In contrast, if $W_0$ is excessively large (3.0 L), the braking force and pressure decrease significantly (with $R$ reduced to approximately 40 kN), resulting in insufficient damping capability at the end of the stroke. Therefore, $W_0$ should be selected within a suitable range (approximately 2.3 - 2.5 L) to effectively limit impulse loads while ensuring structural safety and operational reliability.

## 4. CONCLUSIONS

In this study, a comprehensive mathematical and numerical model has been developed to investigate the dynamic behavior of an artillery recoil system, with particular emphasis on the influence of air entrainment and key structural parameters of the hydraulic recoil braking mechanism.

The analysis demonstrates that the presence of air in the recoil braking chamber has a significant influence on the recoil resistance force characteristics. When air effects are considered, the recoil force profile becomes smoother, the peak force is moderated, and the stable force plateau is extended, leading to a more uniform energy dissipation process. In contrast, neglecting air effects results in an earlier and higher peak recoil force, accompanied by a rapid force decay, which may generate unfavorable impulse loads on the gun structure.

Furthermore, the study reveals that the initial volume of the working chamber in the recoil braking mechanism plays a decisive role in controlling the recoil process. An excessively small initial volume produces high peak forces and pressures that may threaten structural integrity, whereas an overly large volume leads to insufficient damping near the end of the recoil stroke. An appropriate range of the initial working chamber volume is therefore required to ensure safe recoil velocities, acceptable pressure levels, and reliable braking performance.

The proposed methodology provides a useful theoretical and computational framework for evaluating recoil mechanism performance and can support the optimization and reliability improvement of modern field artillery operating under practical firing conditions.

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## TÓM TẮT

### Nghiên cứu ảnh hưởng của không khí trong cơ cấu hãm lùi đến hiệu suất làm việc của pháo khi bắn

*Bài báo nghiên cứu về ảnh hưởng của không khí và các tham số kết cấu của cơ cấu hãm lùi thủy lực đến quá trình bắn và độ ổn định của các hệ thống pháo. Một mô hình toán học được xây dựng nhằm mô tả quá trình thuật phóng trong của pháo và động lực học của các bộ phận lùi trong cả giai đoạn lùi và đẩy lên. Bài báo cũng tính toán ảnh hưởng của không khí trong cơ cấu hãm lùi đến lực cản lùi, vận tốc lùi, hành trình lùi và đặc tính phân bố lực bằng cách đưa vào tính nén được của hỗn hợp chất lỏng - không khí thông qua môđun đàn hồi khối hiệu dụng. Bài báo cũng đã khảo sát ảnh hưởng của thể tích khoang làm việc ban đầu của hãm lùi đến chuyển động của khối lùi. Kết quả mô phỏng với pháo D-44 cỡ 85 mm cho thấy việc bỏ qua ảnh hưởng của không khí sẽ dẫn đến lực cản lùi cực đại lớn hơn và xuất hiện sớm hơn, vùng ổn định của lực cũng ngắn và kém ổn định hơn, do đó có thể gây ra các xung lực bất lợi tác dụng lên kết cấu pháo. Các kết quả nghiên cứu cung cấp cơ sở lý thuyết có giá trị để đánh giá hiệu quả làm việc của cơ cấu hãm lùi, cũng như góp phần nâng cao độ tin cậy, độ bền và hiệu quả bảo đảm kỹ thuật của các hệ thống pháo mặt đất.*

**Từ khoá:** Khe hở giữa vòng điều tiết và cán điều tiết; Điều kiện ổn định; Máy hãm lùi; Pháo.