International Journal of Latest Engineering and Management Research (IJLEMR)
ISSN: 2455-4847
www.ijlemr.com || Volume 10 – Issue 11 || November 2025 || PP. 11-18

Analysis of the Launch Performance of Multi-Stage Electromagnetic Induction Firefighting Projectiles Based on Theoretical Calculations and Experimental Tests

Wang Qian, Liu Fengliang, Yao Zhenmin, Chen Fangyun
[1]*Huate Magnet Group Co., Ltd., Weifang, Shandong Province, China*
[2]*Shandong Provincial Key Laboratory of Intelligent Magnetoelectric Equipment and Mineral Processing Technology, Weifang Shandong Province, China*

Abstract: The multi-stage electromagnetic induction coil fire-fighting projectile launching device generates a large electromagnetic force through the magnetic coupling between the induction coil and the armature coil, driving the fire-fighting projectile armature to be ejected at high speed, enabling precise firing of the fire-fighting projectile and initiating fire-fighting operations.The article first analyzes the working performance of multi-stage electromagnetic induction coils, and based on mathematical models, analyzes the electromagnetic coupling mechanism of single-stage induction coils and multi-stage induction coils. The armature electromagnetic force, armature velocity, current circuit equation, and mutual inductance parameters are analyzed and calculated, and a theoretical calculation model for armature emission velocity under the action of coupled magnetic field is given. Afterwards, the emission speed of the armature under the action of multi-stage electromagnetic coils was experimentally tested, and the velocity changes of the armature under different emission strategies were compared, providing data support for numerical calculation and simulation analysis of multi-stage electromagnetic induction coils.
Keywords: Induction coil、Fire-fighting projectile、Launch、Experimental test、Theoretical calculation

I. Introduction

With the development of the social economy, the risks and losses caused by fires continue to rise, and firefighting faces many new challenges. Urban high-rise buildings have exceeded 300 meters in height; fires involving flammable and explosive materials such as those in the petrochemical industry are highly destructive and dangerous, and traditional water hoses are difficult to handle them. Using electromagnetic coil launchers to launch fire-extinguishing projectiles for firefighting can meet the need for precise and efficient fire control. Studies have shown that, under established structural parameters and control methods, the application of electromagnetic coil launchers in firefighting gun models can ensure excellent dynamic performance.Inductive coil emission is a kinetic energy device that utilizes the principle of electromagnetic induction [1], which generates Ampere force by coupling the magnetic field between the driving coil and the armature coil to drive the armature. Common types of electromagnetic emission devices include single-stage pulse induction coils, synchronous induction coils, and asynchronous induction coils [2]. The multi-stage electromagnetic induction coil device includes a capacitor, an induction coil, and an armature. Based on the electromagnetic coupling effect between the electromagnetic induction coil and the armature coil, the armature is emitted at a higher speed. The basic laws are the electromagnetic coil coupling induction law and Lenz's law, which can achieve electromagnetic projection of larger loads [3].

During the emission process of the multi-stage electromagnetic induction coil device, the magnetic field generated by the electromagnetic induction coil and the magnetic field generated by the armature's own induced current are coupled with each other, resulting in a very complex internal magnetic field and difficulty in accurately calculating the armature emission speed. Based on the multi-stage electromagnetic coil current circuit, Xiang Hongjun analyzed the mathematical formula of the electromagnetic emission device based on multiple transistors, calculated its electromagnetic force function and armature emission function, calculated the magnitude of induced voltage and current in the induction coil based on Lenz's law, and analyzed the coupling characteristics between different induction coils [4]. Jia Qiang conducted simulation analysis on the coupling effect of multi-level electromagnetic coil electromagnetic induction structure and analyzed the coupling model of inter level coil effect in multi-level coil device [5]. S Gao analyzed and calculated a non-contact electromagnetic gun with an armature module, which can increase the armature from 0m/s to 60m/s [6]. CD Sijoy analyzed the mathematical model of the electromagnetic induction coil, which can calculate the changes in the armature motion equation and analyze the electromagnetic effect, electromagnetic force, coil device, and armature structure. The experimental results matched the calculated values [7]. S Madhavan conducted computational research using materials, coils, and circuit parameters commonly used in experiments, and analyzed the working limit at which electromagnetic induction coils can survive in their operating state [8]. Based on the above analysis, the article further clarified the expression of armature velocity under magnetic field coupling, and tested the emission velocity of the multi-stage electromagnetic induction coil device through experiments, analyzing the emission performance of the multi-stage electromagnetic induction coil on the armature.

The article first analyzes the working performance of multi-stage electromagnetic induction coils, and based on mathematical models, analyzes the electromagnetic coupling effect of single turn coils and single pole induction coils. The armature electromagnetic force, armature velocity, current circuit equations, and mutual inductance parameters are calculated, and a calculation model for armature velocity under the action of a coupled magnetic field is given. Afterwards, based on experimental analysis, the emission performance of multi-stage electromagnetic coils on the armature was studied, and the velocity changes of the armature under different emission strategies and the action of electromagnetic coils were analyzed.

II. Multi Level Coil Electromagnetic Coupling Calculation

During the emission process of multi-stage electromagnetic induction coils, there is a coupling effect between the induction coil and the armature coil. Different stages sequentially generate electromagnetic forces on the armature. To simplify the analysis, the expression for the coupling effect between the induction coil and the armature coil is calculated using a single turn coil as an example.Based on Ampere's force, it can be inferred that the electromagnetic force acting on the armature coil can be decomposed into two directions: the direction of motion and the central direction. The force acting on any point of the armature coil in the direction of motion can be expressed as [9]

$$dF_x = I_2 \cdot dl \times B_r \tag{1}$$

Among them, I_2 is the current on the armature coil, and B_r is the magnetic induction intensity.

The electromagnetic force in the central direction can be expressed as

$$dF_r = I_2 \cdot dl \times B_x \tag{2}$$

Among them, I_1 is the current on the induction coil, and B_x is the magnetic induction intensity. The coil circuit diagram is shown in Figure 1 [10-15].

The electromagnetic force in the center direction of the coil can be expressed as the superposition of armature gravity and electromagnetic force. Integrating the forces in different directions along the surface of the armature coil can obtain a numerical solution, but the calculation process is relatively complex, and the virtual displacement method can be used to solve the electromagnetic force [9].

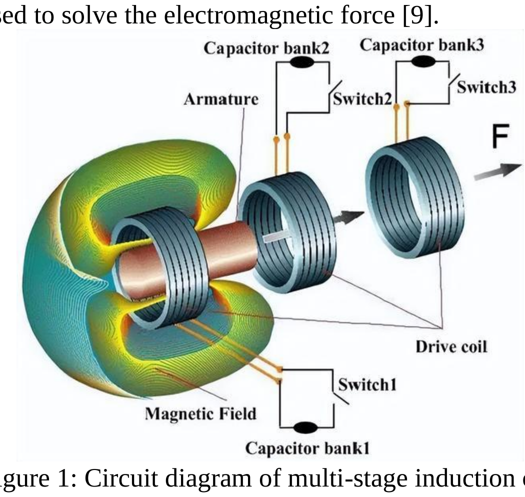

Figure 1: Circuit diagram of multi-stage induction coil

If the current value of the electromagnetic induction coil is I_1, the self inductance of the coil is L_1, the magnetic flux generated by the self inductance of the induction coil is ψ_1, the mutual inductance of the electromagnetic induction coil to the armature coil is M_{21}, the current value in the armature coil is I_1, the self inductance of the armature coil is L_1, the magnetic flux generated by the armature coil is ψ_2, and the mutual inductance of the armature coil to the electromagnetic induction coil is M_{12}, then the magnetic flux of the interaction between the electromagnetic induction coil and the armature coil current can be expressed as

$$\begin{cases}\psi_{21} = M_{21} I_1 \\ \psi_{12} = M_{12} I_2\end{cases} \tag{3}$$

Combining equations (1) to (3), the total magnetic energy of the electromagnetic coil and the driving coil circuit is obtained as

$$W = \frac{1}{2}\sum_{i=1}^{2} I_i \psi_i + \frac{1}{2} I_1 \psi_{12} + \frac{1}{2} I_2 \psi_{21} = \frac{1}{2}\sum_{i=1}^{2} I_i \psi_i + \frac{1}{2} I_1 I_2 M_{12} + \frac{1}{2} I_2 I_1 M_{21} \tag{4}$$

Based on the law of energy conversion, electromagnetic energy W will be converted into the kinetic energy of the armature and a small amount of other energy. When t=0s and the armature velocity is 0, electromagnetic energy can be expressed as the sum of armature kinetic energy and other energy. Ignoring other input energies, electromagnetic energy can be expressed as the path integral of electromagnetic force in the direction of armature motion. Combining the above equation, we can obtain

$$W = W_1 + W_2 = \int_0^x F_x dx = \frac{1}{2}\sum_{i=1}^{2} L_i I_i^2 + M_i I_1 I_2 \tag{5}$$

In the equation, the coil inductance and coil current are constants relative to path *x*. By differentiating path *x* from the above equation, the electromagnetic force of the armature coil in the direction of motion can be obtained

$$F_x = \frac{dM_i}{dx} I_1 I_2 \tag{6}$$

Further analysis of the above equation yields the expressions for single-stage multi turn electromagnetic induction coil and armature coil. Combined with Figure 1, assuming a capacitor voltage of u_C , an electromagnetic induction coil voltage of u_1, an armature self inductance voltage of u_2, an electromagnetic induction coil current of i_d , and an armature coil current of i_p , at *t*=m, the single-stage electromagnetic induction coil circuit and electromagnetic force can be expressed as

$$\begin{cases} L_1 \frac{di_d}{dt} - M_i \frac{di_p}{dt} - \frac{dx}{dt} i_p \frac{dM_i}{dt} + R_d i_d = u_C \\ F_m = \left(\frac{dM_i}{dx}\right)_m I_{pm} I_{dm} = \frac{d}{dx}\left(L_1 i_d - \int_0^t u_c dt + \int_0^t R_d i_d dt\right)_m I_{pm} I_{dm} \end{cases} \tag{7}$$

The above equation is the expression for a single-stage electromagnetic induction coil, while the theory for a multi-stage induction coil is basically the same. When the armature passes through the previous stage electromagnetic induction coil and moves at a higher initial velocity to the second stage induction coil, the discharge sequence is controlled, and the second stage induction coil generates a magnetic field, causing the surface of the armature to induce current again, thereby generating electromagnetic force in the direction of motion. Compared with a single-stage coil, multi-stage induction coils generate mutual inductance between different induction coils. Based on the above equation, the voltage equation for the second stage electromagnetic induction coil and the expression for the electromagnetic force in the direction of armature motion can be obtained

$$\begin{gathered} L_{d2} i_{d2} - u_{C2} + \int_0^t R_{d2} i_{d2} dt = \int_0^t i_p dt M_{d2} + \int_0^t M_{d2} dt i_p - M_{d2} i_{d2} \\ F_m = \sum_{i=1}^{2}\left(\frac{dM_{di}}{dx}\right)_m I_{p2m} I_{d2m} \end{gathered} \tag{8}$$

If the mass of the armature is m_p, the initial velocity is v_0, the instantaneous acceleration is *a*, and at time t=m, the motion equation of the armature can be expressed as

$$\begin{cases} x = v_0 + \frac{1}{2}\int_0^m a_m dt \cdot t^2 \\ F_m = m_p a_m \\ v = v_0 + \int_0^m a_m dt \cdot t \end{cases} \tag{9}$$

Based on the equations of inductance, self inductance, mutual inductance, and voltage of the electromagnetic induction coil and armature coil, the instantaneous acceleration and velocity of the armature can be solved using the above equation

$$\begin{cases} a_m = \dfrac{F_m}{m_p} = \dfrac{1}{m_p}\sum_{i=1}^{2}\left(\dfrac{dM_{di}}{dx}\right)_m I_{p2m} I_{d2m} \\ v_p = v_0 + \dfrac{1}{m_p}\int_0^m \sum_{i=1}^{2}\left(\dfrac{dM_{di}}{dx}\right)_m I_{p2m} I_{d2m} dt \end{cases} \tag{10}$$

III. Experimental Testing and Analysis

3.1 Single stage electromagnetic induction coil testing

Conduct tests on the remote vehicle-mounted fire extinguishing device using fire simulation projectiles, primarily to verify the device's fire-firing performance and practical feasibility. The device features a modular box design, with each functional unit independently enclosed within a container, offering advantages of easy assembly and flexible combination. The core system includes a central control unit, charging unit, pulsed discharge unit, two-degree-of-freedom gimbal, and a seven-level load coil.

The charging unit is equipped with an 80kW charger. After being connected to a 380V AC power grid, it converts the AC to high-voltage electricity through inverter rectification, supplying power to the 5000μF/10kV energy storage capacitor of the pulse discharge unit. The pulse discharge unit integrates key components such as a mechanical switch, snubber resistor, semiconductor thyristor, high-voltage divider, and current collector, forming a complete energy conversion and release circuit, as shown in Figures 2 and 3.

Testing is carried out in accordance with fire operation safety standards: When the energy storage capacitor is charged to the preset voltage, the central control unit automatically stops charging and disconnects the charging switch. It then outputs 7 optical signals to trigger the thyristor conduction, quickly discharging the stored energy to the load coil while simultaneously collecting key parameters such as voltage and current in real time. After the discharge is complete, the central control unit activates the mechanical discharge switch, safely releasing the remaining energy through the discharge resistor to prevent residual energy from causing safety hazards.

Figure 2: Actual Photo of the Modular Unit of the Vehicle-Mounted Remote Fire Extinguishing Device

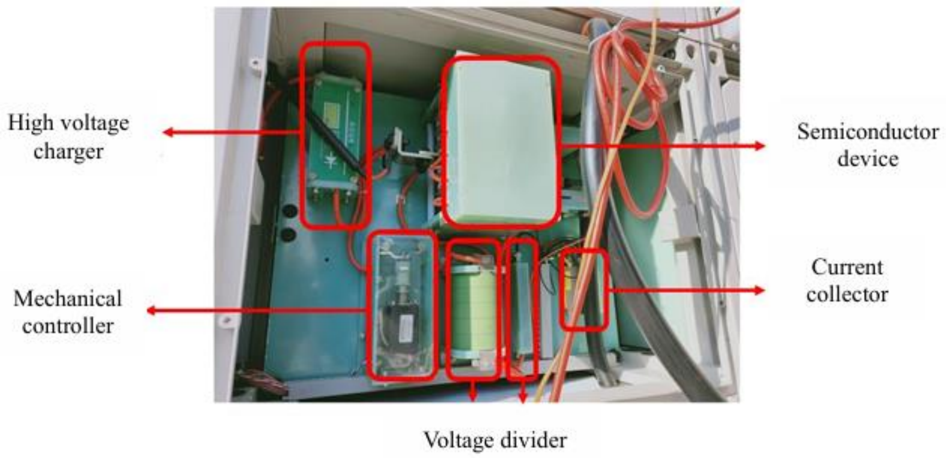

Figure 3: Physical Diagram of the Pulse Discharge Module

The two-degree-of-freedom gimbal can achieve horizontal rotation and elevation adjustment. Two hydraulic machines and two hydro-pneumatic shock absorbers are arranged between it and the load coil, effectively counteracting recoil during the firing process and ensuring the stability of long-range fire extinguisher projectile deployment. The control unit's upper computer interface integrates functions such as charging communication, trigger control, switch operation, and parameter acquisition and display, ensuring full-process visualization and precise control during testing, as shown in Figure 4.

Figure 4: Physical View of the Gimbal and Output Load

To verify the normal operation capability of the single-stage electromagnetic induction coil at 7500V voltage, a 7.5kV discharge test was conducted on the induction coil load. During the experiment, a 15kg armature was used for testing, with chromium zirconium as the load-bearing material, an outer diameter of 120mm, a thickness of 10mm, and a height of 100mm. The counterweight was mainly made of epoxy resin material.

The speed measurement device is set at the exit position and uses dual light curtains for collection. The distance between the two light curtains is 289mm. By measuring the time it takes to pass through the two light curtains, the exit speed of the armature can be calculated. During the experiment, the distance between the tail of the armature and the tail of the thruster was 97mm. During the charging process, only the first group of pulse discharge units were charged and discharged. The detailed parameters are shown in Table 1.

Table 1: Single stage coil propulsion parameter table

Parameter name	Numerical value	Parameter name	Numerical value
Capacitor charging voltage	7.5(kV)	Coil charging current	0.5(A)
Armature diameter	122(mm)	Armature thickness	10(mm)
Armature material	Chromium Zirconium Copper	Armature height	100(mm)
Armature weight	15(kg)	Position of armature	97(mm)
Experimental trigger voltage	7605(V)	Peak value of experimental current	15.544(kA)

The discharge time of the first stage coil with a discharge current of 7.5kV is 0.00ms, and the maximum current is obtained at 2.293ms, with a maximum current of 15.544kA. As shown in Figure 5, the output velocity waveform of the simulated armature under a discharge voltage of 7500V is obtained. The armature passes through the first light curtain for 42.9ms and the second light curtain for 50.85ms, and the calculated output velocity is 36.34m/s.

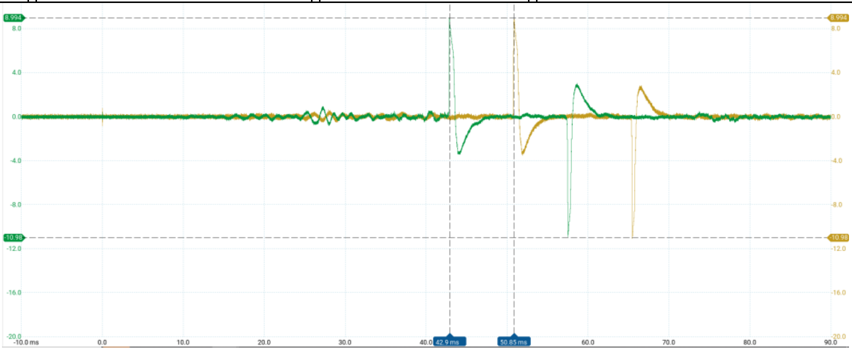

Figure 5: Measurement waveform of armature emission speed of single-stage induction coil

3.2 Multi level electromagnetic induction coil testing

To test the propulsion phenomenon of the armature under the discharge condition of multi-stage electromagnetic induction coil timing, a two-stage propulsion test was designed, with the propulsion timing of the first and second stage coils being 0.00ms and 2.8ms respectively. The charging voltage was 7.5kV, and during the test, a 15kg armature was used, with a force material of chromium zirconium, an outer diameter of 120mm, a thickness of 10mm, and a height of 100mm. The counterweight was mainly made of epoxy resin material.

The speed measurement device is set at the exit position and uses dual light curtains for collection. The distance between the two light curtains is 289mm. By measuring the time it takes to pass through the two light curtains, the exit speed of the armature can be calculated. During the experiment, the initial position of the armature was the same as that of the single-stage coil, and only the first two groups of pulse discharge units were charged and discharged during the charging process. The detailed parameters are shown in the table below.

Table 2: Parameters of Multi level Induction Coil Propulsion

Parameter name	Numerical value	Parameter name	Numerical value
Capacitor charging voltage	7.5(kV)	Coil charging current	0.5(A)
Armature diameter	122(mm)	Armature thickness	10(mm)
Armature material	Chromium Zirconium	Armature height	100(mm)
Armature weight	15(kg)	Position of armature	97(mm)
Experimental trigger voltage	7605(V)	Peak value of experimental current	15.478(kA)

During the experiment, the discharge time of the first stage induction coil was 0.00ms, and the discharge time of the second stage was 2.8ms. The maximum current was obtained at 2.166ms, with a maximum current of 15.478kA, as shown in Figure 6.

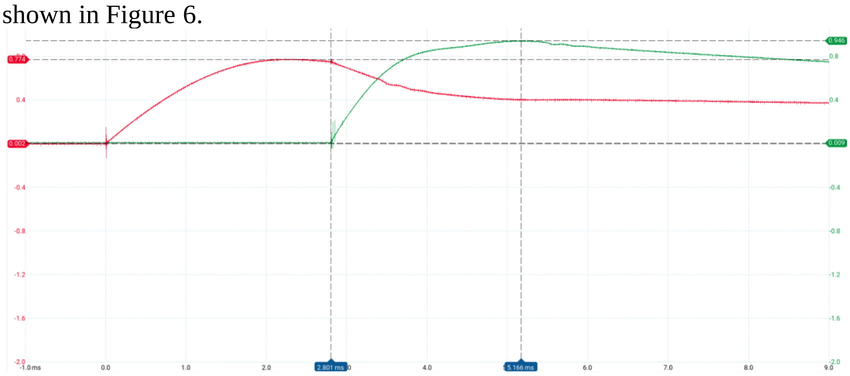

Figure 6: Measurement waveform of multi-stage induction coil current

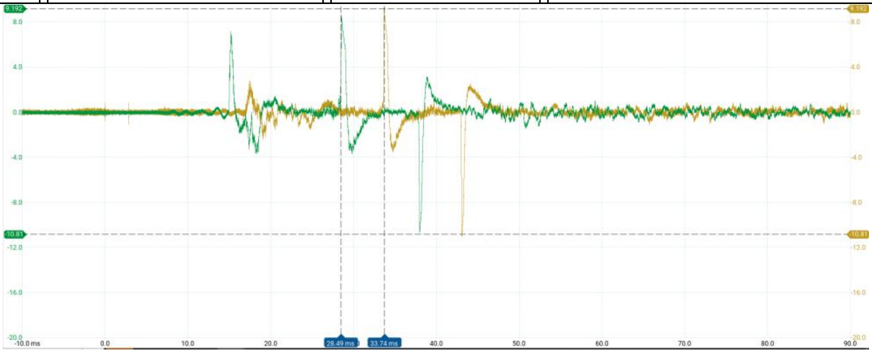

Figure 7: Measurement waveform of armature emission speed of multi-stage induction coil

Figure 7 shows the emission velocity waveform of the armature under a discharge voltage of 7500V. The armature passes through the first light curtain for 28.49ms and the second light curtain for 33.47ms, and the calculated exit velocity is 55.1m/s.

IV. Conclusion

The article analyzes the operational performance and electromagnetic coupling mechanism of a multi-stage electromagnetic induction coil fire-fighting projectile launch system. Combined with experimental testing, it clarifies the launch speed characteristics of the fire-fighting projectile armature under the action of multi-stage electromagnetic coils, providing essential data support for the numerical calculation, simulation optimization, and practical application of this type of fire-fighting equipment.

(1) Based on the armature electromagnetic force, armature velocity, current circuit equation, and mutual inductance parameters, a new theoretical calculation expression for armature emission velocity is proposed, which reduces the complexity of solving armature velocity using traditional formulas.

(2) Based on experimental testing, the emission speed of the armature under the action of a single-stage electromagnetic coil was obtained. The peak current of the 15kg chromium zirconium armature at 7500V was 15.544kA, and the emission speed was 36.34m/s.

(3) Based on experimental testing, the emission speed of the armature under the action of multi-stage electromagnetic coils was measured. When the number of electromagnetic coil stages was 2, the emission speed of the armature significantly increased. At a voltage of 7500V, the peak current of the 15kg chromium zirconium armature was 15.4kA, and the emission speed increased to 55.1m/s.

References

[1] Narevicius E, Libson A , Parthey C G, et al. Stopping Supersonic Beams with a Series of Pulsed Electromagnetic Coils: An Atomic Coilgun [J]. Physical Review Letters, 2008, 100(9):093003.

[2] Wang Qiusheng, Li Xin, Xu Xin Research on Induction Power Supply Technology for Fuze Mounds [J]. Journal of Detection and Control, 2005, 27 (3): 5

[3] Huang Xiaolong, Wang Dongfang Structural optimization and simulation of the converging end of a small caliber irregular coil gun [J]. Journal of Zhongyuan Institute of Technology, 2020, 31 (3): 6

[4] Xiang Hongjun, Zhao Keyi, Li Zhiyuan, etc Inter stage coupling characteristics of multi-stage electromagnetic induction coil gun [J]. High Voltage Technology, 2012, 38 (5): 6.

[5] Jia Qiang, Guan Xiaocun, Gong Xiangping, etc Analysis of Electromagnetic Force Coupling between Multistage Electromagnetic Induction Coil Guns [J]. Journal of Artillery Launch and Control, 2023, 44 (1): 6

[6] Shunshou G, Chengwei S, Yingshi C, et al. Experimental study on non-contact helical tube for 60mm projectile [J]. Chinese Journal of High Voltage Physics, 1996.

[7] Sijoy C D .Numerical Simulations of an Electromagnetic Coilgun for Impact and Fracture Studies [J]. American Institute of Physics, 2011.

[8] Madhavan S, Sijoy C D, Pahari S, et al. limits imposed by solenoid damage on the maximum velocity achieved by an electromagnetic coilgun: A computational study [J]. American Institute of Physics, 2012.

[9] Fullem T Z, Benedict M S .A Simple Implementation of an Electromagnetic Coilgun Using a Camera Flash Circuit [J].Physics Teacher, 2009, 47(3):181-183.

[10] Narevicius E, Parthey C G, Libson A, et al. An atomic coilgun: using pulsed magnetic fields to slow a supersonic beam [J]. New Journal of Physics, 2007, 9(10):358.

[11] Zhang Chaowei, Deng Qibin, Tang Lei, etc Characteristics analysis of synchronous induction coil gun armature [J]. Journal of Artillery Launch and Control, 2011 (3): 5

[12] Zou Bengui, Cao Yanjie, Liu Wenbiao, etc Research on Optimization of Multi level Synchronous Induction Coil Gun Drive Coil [J]. Journal of Naval Aviation Engineering College, 2009, 24 (6): 4
[13] Zhao Keyi, Li Zhiyuan, Cheng Shukang, etc Finite Element Analysis of Magnetic Field and Eddy Current Field inside Synchronous Induction Coil Cannon [J]. High Voltage Technology, 2008.
[14] Zhang Yadong, Xiong Min, Dong Mingyang, et al. Research on Electromagnetic Catapult Fire Suppression Bomb Firefighting System [J]. High Power Laser and Particle Beams, 2020, 32(02):127-132.
[15] Liu Shaogang, Qiu Bo, Pang Yonggang. Research on Electromagnetic Catapult Forest Firefighting Cannon [J]. Journal of Beijing Forestry University, 2010, 32(01):108-113. DOI:10.13332/j.1000-1522.2010.01.015.