Research Article

Research on Vehicle-Mounted Electromagnetic Ejection Remote Fire Extinguishing System

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This article first introduces the characteristics and disadvantages of traditional remote fire extinguishing technology and proposes a remote fire extinguishing system based on electromagnetic ejection. Based on the finite element analysis method and the grid matrix method, a seven-segment electromagnetic launcher model is designed. As the initial energy source, the capacitor can accelerate a 10 kg fire extinguishing bomb to 113 m/s with a range of 2 km. The results show that the electromagnetic catapult designed in this study can meet the needs of fire extinguishing bombs. This paper also designs the overall structure of the vehicle electromagnetic catapult remote fire extinguishing system, discusses its role in the field of firefighting, and prospects the future work.

1. Introduction

The traditional long-range fire extinguishing techniques are shoulder-fired, air-propelled, air-dropped, artillery, and rocket-propelled. The shoulder-mounted type generally means that firefighters carry water guns and fire extinguishers and other fire extinguishing equipment into the fire scene. The water gun is connected to the fire truck through a hose. After the firefighters enter the fire site, the water in the fire truck is pumped to the fire site by a water pump, and the water gun is sprayed to extinguish the fire. The original fire extinguishing technology can only extinguish low-altitude and short-distance fires but does not perform well on long-distance and ultrahigh fires. Therefore, various fire extinguishing bombs for long distance fires have been developed at home and abroad. Fire extinguishing bombs are launched into the fire site by fire extinguishing guns, aircraft, etc., and detonate at the right time to disperse the fire extinguishing agent in the bomb to the fire site for extinguishment. Compared with fire extinguishing equipment such as cloud ladders, fire extinguishing bombs are more mobile, and the fire extinguishing height can reach hundreds of meters, without being affected by the surrounding environment.

1.1. The Research Status. Hungarian engineers invented a fire extinguishing bomb with a large caliber, long-range, large capacity, and continuous firing [1]. In 2001, Russia refitted the BTR-80 vehicle into a fire extinguishing vehicle, the model is GAZ-5903, which can continuously launch 22 fire extinguishing bombs with a range of 50 ~ 300 m and can extinguish three types of explosive dangerous goods A, B, and C fire. The fire extinguishing vehicle adopts the military fire control system with a high level of automation [2]. In 2005, Italy developed an air fire cannon with strong mobility and a maximum firing range of up to 200 m, but it could not fire continuously and the fire extinguishing efficiency was low [3]. Germany has developed a fire extinguishing missile, which can carry 500 kg of foam fire extinguishing agent and spray continuously for 20 ~ 30 s. The fire extinguishing
As a helpful assistant, I can provide the text as follows:

In 2006, Qingguo proposed a PJ120 type pneumatic fire extinguishing gun with a weight of 32.4 kg, a range of 180 m, a vertical height of 100 m, and a maximum range of impact point dispersion radius of 6.5 m. The diameter of the fire extinguishing bomb is 120 mm, the weight of the fire extinguishing bomb is 4.6 kg, the mass of extinguishing agent is 3 kg, and the maximum fire extinguishing area is 9 m². In 2010, the 710 Research Institute of China Shipbuilding Industry Corporation developed the “CMH-1 Remote Intelligent Forest Fire Extinguishing System,” with a maximum range of 600 m; it is a single bomb which can spread an area of not less than 100 m² with a salvo fire extinguishing range not less than 1000 m²; the fire extinguishing bomb has a net weight of 17 kg and adopts Doppler-fixed height, where timing and impact fuzes and is filled with a self-developed high-efficiency liquid water glue fire extinguishing agent. It is suitable for extinguishing large-scale fires in forests and grasslands. In 2011, Nanjing University of Science and Technology proposed a 105 mm vehicle-mounted multitube fire extinguishing gun device, which uses the mortar firing method to shoot fire extinguishing shells at high speed with a chamber pressure of 20 MPa, a projectile’s initial velocity of 125 m/s, a projectile weight of 7495 g, and a range of 2 km. The width of the device is 1825 mm, and the load weight is 1820 kg. In 2014, Harbin Engineering University developed a pneumatic fire extinguishing gun, which uses aerodynamic force without gunpowder to launch fire extinguishing bombs. A single gas cylinder is 50 L with 4 rounds/min, and has an exit speed of 93.1 m/s. In 2015, the 206 Institute of Aerospace Science and Industry Corporation developed the projectile type dry powder fire truck for high-rise buildings. The firing height range is 100 to 300 m, the maximum elevation angle is 70°, and the firing distance is 1 km. There are 24 combined fire extinguishing bombs on the launching module, and each bomb is equipped with 3.6 kg of ultrafine efficient fire extinguishing agent, and one fire extinguishing bomb can cover 60 m³ of space. In 2016, North University of China carried out kinematics and dynamics simulation analysis on fire extinguishing projectile launched by an air cannon. The mass of fire extinguishing projectile is 5 kg, the diameter of projectile body is 120 mm, and the total length is 1150 mm.

At present, the most widely used in the field of fire fighting is the China Aerospace Science and Industry Corporation multipipe fire-fighting system for high-rise buildings developed by the Second Institute of Fire Control. Fire-fighting bombs are fired in the form of rockets into the walls of high-rise buildings or the interior, which are equipped with gunpowder at the end and detonating device at the head. The fire-extinguishing operation is carried out by blasting the fire-extinguishing bomb in the fire field. Fire extinguishing operations are carried out by blasting fire bombs. 24 fire bombs are integrated in the single vehicle, and the fire extinguishing height is 300 meters. The disadvantage is that the muzzle velocity of fire bombs cannot be regulated, and the safety of firing with gunpowder is not easy to guarantee.

1.2. Problems Existing in the Fire Extinguishing System. In recent years, the remote fire extinguishing system has made great progress, and the fire extinguishing distance, height, and coverage area have all been improved. However, the traditional remote fire extinguishing system has its natural limitations, which are manifested in the following aspects:

(1) **High Cost of Construction and Poor Continuity.** The carrier cost of airborne long-range fire extinguishing technology based on UAV and aircraft is too high, which results in its failure to be fully popularized. In addition, limited by the size of the carrier, the quantity of fire extinguishing agents that can be carried at one time is less than that carried by land equipment, so its continuous fire extinguishing performance is poor.

(2) **Insufficient Range.** With the increasing pace of urbanization, the number of super high-rise buildings is increasing, which is also an important scene of fire. In order to ensure the safety of firefighters, the range of remote fire extinguishing technology should be further increased. If the range is increased, the air pressure will be increased, which will increase the...
weight of the launcher and reduce the flexibility and mobility of the air thrust equipment.

(3) Large Potential Safety Hazard of Explosive Devices. The rocket-propelled long-range fire extinguishing system relies on gunpowder to be propelled. As the gunpowder is a kind of explosive product, it is strictly controlled. The purchase of gunpowder requires the approval of relevant departments, and there are strict requirements for storage, so the rocket-propelled fire extinguishing system cannot be commercialized. Its use is strictly restricted, cannot be close to the dangerous and explosive petrochemical products, and also cannot be close to the fire scene; otherwise, it is easy to become the source of fire. Artillery and rocket-propelled versions require increased gunpowder, but residual gunpowder can cause a secondary fire.

1.3. Technical Route. This research adopts the research route as shown in Figure 1 [7]. Through the design of the main structure and control module of the electromagnetic ejection system, the mathematical model is constructed to determine the parameters, and the simulation is conducted to test the simulation effect.

2. Electromagnetic Ejection Remote Fire Extinguishing Technology

2.1. Electromagnetic Ejection Technology. Aiming at the problems of remote fire extinguishing technology mentioned above, this paper proposes a remote fire extinguishing technology based on vehicle electromagnetic launch. Electromagnetic emission technology is a revolution of the launch mode after the launch of mechanical energy and chemical energy. It uses electromagnetic force (energy) to propel the object to a high speed or ultrahigh speed launch technology. By transforming the electromagnetic energy into the instantaneous kinetic energy required by the launch load, it can accelerate the load from grams to dozens of tons of high speed in a short distance and break the speed and energy limit of the traditional launch mode, which is the inevitable part of the future launch mode [8]. Electromagnetic coil propulsion occurs with the primary application of strong pulse current, forming secondary synchronous or asynchronous electromagnetic traveling wave and the projectile induced by the eddy current interaction to achieve the projectile acceleration. Electromagnetic catapult by electromagnetic propulsion has the advantages of long range, high launch frequency, strong persistence, and ability to realize cold launch, low operating cost, and easy operation and maintenance.
The Sandia Laboratories in the United States is one of the first laboratories in the world to study electromagnetic catapult [9]. As early as 2007, Sandia Laboratories carried out research on the electromagnetic gun project, using a synchronous coaxial coil launcher, and 45 coils were synchronized to form a 3.7-meter-long gun barrel with a caliber of 120 mm, and the 18 kg M934 mortar simulation projectile was pushed to the exit speed of 424 m/s. In China, the Institute of Electrical Engineering of Chinese Academy of Sciences has also carried out related research, and developed a 4-segment coil transmitter that can launch objects with a mass of 5 kg to 500 m/s [10]. It can be seen that electromagnetic ejection technology has been studied deeply and can be applied in the field of remote fire suppression.

Electromagnetic catapult technology has rich application scenarios. In military, it is used as an ultrahigh speed kinetic energy weapon [11] for strategic defense and tactics. In the aerospace field, it can be used for ground-to-air directional launch rockets and pure payloads, and in space, it is used to promote spacecraft to carry out orbit transfer in the field of remote fire suppression.
transportation, using the principle of electromagnetic launch electromagnetic train, using the original railway track, and its cost is only 1/4 of that of the magnetic levitation train. In industries, it can be used to make electromagnetic pumping unit so as to improve pumping efficiency and reduce cost. In addition, electromagnetic force can launch ultrahigh speed projectiles, so it can be used as a means and tool for high-pressure physics experiments and controlled nuclear fusion research.

2.2. Principle and Modeling of Electromagnetic Ejection. At present, there are two main methods to study coil gun: circuit model analysis method and finite element method [12]. In this study, finite element analysis and the grid matrix method were used. Due to the skin effect, the induced current distribution on the electrical pivot section is not uniform. If the armature is divided into \( m \) concentric rings, then when the axial cross-sectional area of the ring is small enough, the induced current can be considered to be evenly distributed on the cross section; that is, \( m \) loops are used to make it equivalent to the original armature. We can assume that the excitation coils have a total of \( k \) stages.

Figure 2 shows the basic process of electromagnetic ejection. Figure 3 is the equivalent circuit model. The excitation current is transient in the firing process of the coil gun, and the lumped parameter model of each coil can be established with the parameters of resistance, self-induction, mutual induction, inductance gradient, etc. Finally, the lumped parameter model can be summed up as the initial value problem of the nonlinear variable coefficient ordinary differential equation. The primary notations used in this paper are listed in Table 1 [15–20].

The ordinary differential equation can be established by the grid matrix method:

\[
(R + M) \frac{d}{dt} \mathbf{V}_c - R \mathbf{I} - v \frac{d}{dt} \mathbf{M}_I. \tag{1}
\]

The relation between capacitor voltage and excitation current is

\[
C \frac{d \mathbf{V}_c}{dt} = -I_d. \tag{2}
\]

The motion governing equation of the coil emitter system is

\[
m_p \frac{dx}{dt} = \sum \frac{I_p \frac{pd}{dx}}{I_p} \tag{3}
\]

\[
\frac{dx}{dt} v. \tag{4}
\]

2.3. Simulation and Experiment of Electromagnetic Coil Propulsion. In this study, a seven-section electromagnetic coil ejection device is designed. Each segment consists of six coils, and each coil is wound by solid copper wire. The diameter of the emitter is 120 mm, and the total length is 1 m. The structure of the ejection device is shown in Figure 4 [13].

This research adopts the simulation program [14] of the process, as shown in Figure 5, the first input system parameters, and the calculation system matrix. The input system parameters include the drive coil geometry, projectile geometric parameters, material parameters of the driving coil and projectile, the drive coil on the number of segments and its connection mode, each power supply parameters, calculation of system parameters including the self-inductance, mutual inductance, resistance, and the fragmentation of the projectile self-inductance, mutual inductance and resistance. Then, according to the different connection modes of the drive coils, the parallel or series calculation models are selected to calculate the trigger delay between phases. Then, by solving the differential equations, the voltage, current, displacement, velocity, acceleration, and the temperature rise of the projectile and the driving coil are obtained. Then, judge whether to leave the coil or not [21–25]. If so, calculate the energy error of this section, average temperature rise, kinetic energy conversion efficiency, etc. If not, the time step is increased, and the variables of the differential equation are recalculated. When leaving the coil of this stage, judge whether to leave the final coil. If leaving, output results and the process will be terminated. If not, increase the number of segments of the driving coil, take the projector current, displacement, and time variables as the system parameters input of the next segment of the driving coil, and start the process again [26–30].

Figures 6 ~ 7 show the simulation and experimental results of the three-phase capacitor current. The black line represents the experimental results, the red dotted line represents the mesh matrix, and the blue line represents the simulation results of the finite element method. The picture shows the velocity and force of the projectile as it passes through the 7-stage electromagnetic coil emitter.

It can be seen from the figure that the initial velocity of the projectile in the first to seventh stages is 13 m/s, 42 m/s, 84 m/s, 104 m/s, 112 m/s, 112 m/s, and 113 m/s, respectively. The maximum axial force of the projectile in the third stage is 47 kN. Compared with the results of finite element analysis, the mesh matrix, and the actual test, it can be found that the simulation results fit well with the experimental results.
3. Vehicle-Mounted Electromagnetic Catapult Extinguishing System

Based on the above simulation results of electromagnetic ejection and existing firefighting technology, we propose a vehicle-mounted firefighting system based on electromagnetic ejection [30, 31]. The overall structure is shown in Figure 8:

The whole system consists of five parts: vehicle body, launching power supply, electromagnetic propulsion device, projectile body loading device, and diesel generator. The operating principle of the remote fire extinguishing system is shown in the figure below. Considering the power consumption problem in areas with insufficient power, the diesel generator is used as the secondary power supply and connected to the charging module to supply energy to the system. The charging module is connected to the energy storage capacitor, and the capacitor is charged after the charging module is charged. The laser rangefinder sends the position signal to the discharge control module, and the central controller controls the capacitor discharge to complete the emission as the driving coil function [32, 33].
Figure 6: Simulation and experimental results of capacitive three-phase current.

Figure 7: Variation of velocity and thrust of the fire extinguishing projectile.

Figure 8: Overall structure of vehicle-mounted electromagnetic catapult remote fire extinguishing system.
The system has the following characteristics:

1. Vehicle-mounted electromagnetic coil launch technology, long-distance throwing efficient special fire bombs
2. To ensure the safety of operators, with high fire extinguishing efficiency, low operating cost, and easy operation and maintenance
3. No relevant products in the field of fire protection promote the development of fire protection equipment

The electromagnetic catapult on-board fire extinguishing system proposed in this study has the following advantages compared with the aforementioned on-board multipipe fire extinguishing system:

1. The equipment is small in size and can pass through narrow streets, which is conducive to quick rescue
2. Electromagnetic propulsion can launch heavier shells and has flexible distance adjustment, and the fire extinguishing effect is more obvious
3. It can realize joint control with the UAV system, dynamically collect fire site information, formulate flexible fire extinguishing plan, realize unmanned fire site operation, and ensure the life safety of frontline firefighters

4. Summary and Prospect

4.1. Summary. In view of the severe fire situation facing the world at present, this paper analyzes the characteristics and existing problems of the traditional remote fire extinguishing technology and puts forward the scheme of using an electromagnetic catapult to the launch fire extinguishing projectile. The seven-stage catapult is adopted, which can shoot at 2 km with the 10 kg fire extinguishing projectile, and the exit speed can reach 113 m/s to meet the demand of remote fire extinguishing. Finally, this study also designed the overall structure of the vehicle-type fire extinguishing system, which can not only be used for firefighting of dangerous chemicals, toxic, explosive, high voltage, and other fires but also be used for firefighting and rescue of high-rise buildings, effectively reducing fire and rescue casualties.

4.2. Discussion. At present, the research on fire cannon is not sufficient in the academic circle, but the fire bombs used are mostly fired under the action of gunpowder or high-pressure gas, which limits the weight of the fire extinguishing agent carried and the effect of fire extinguishing. On the basis of summarizing the current research achievements of electromagnetic ejection, this paper studies the vehicle electromagnetic ejection fire extinguishing system, which is a new type of firefighting equipment. The vehicle-mounted electromagnetic ejection fire extinguishing system is driven by electric power. Through the action of electromagnetic force, the fire extinguishing projectile can advance rapidly in the gun barrel and finally launch. Compared with other fire guns, the vehicle electromagnetic catapult fire extinguishing system uses electromagnetic propulsion, and it can fire more heavy fire bomb, so the fire extinguishing effect will be more obvious.

4.3. Summary. Compared with other fire guns, the vehicle-mounted electromagnetic catapult fire extinguishing system has many incomparable advantages, but it is still in the preliminary research stage, and there are many problems to be solved:

1. Structural design and optimization of vehicle-mounted electromagnetic ejection system
2. Thrust fluctuation problem
3. Heating during launch, etc.

Further research is needed on these issues in the future.

Data Availability

All data generated or analyzed during this study are included in this article.

Disclosure

Xing Wang, Yadong Li, and Zhenrui Shi are cofirst authors.

Conflicts of Interest

The authors declare no conflicts of interest.

References


