Research on Liquid CO_2 Phase Transition Ejection Technology

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Abstract. Due to the low temperature and clean gas, liquid CO_2 phase transition ejection technology has outstanding advantages such as high versatility, low launch cost, and environmental friendliness, which will open up a new research field for the development of missile launch technology. Through the study of phase transition characteristics of liquid CO_2 in this paper, a mathematical model of internal ballistics of the liquid CO_2 phase transition ejection power system is established. And through simulation calculation, the launching parameters such as the pressure in the launcher, the velocity and acceleration of the missile are obtained, and they is compared with the experiment data to verify the validity of the model.

1 Introduction

At present, there are still two ways to launch underwater, that is, water ejection from underwater (cold launching) and direct ignition launch (hot launching). From the characteristics and development of various launch power systems in various countries around the world, it can be seen that ejection has obvious advantages in the launch of airborne, shipborne or submarine missiles, and is the trend of future development[1]. Ejection launch has experienced a variety of different launch power sources, from gun type, hydraulic type, compressed-air type, hydraulic-pneumatic type to gas type, gas-steam type and electromagnetic type being developed. Each power source has its own advantages and disadvantages, as shown in Table 1.

Table 1. Advantages and Disadvantages of Different Power Sources

Power Sources	Advantages	Disadvantages
Gun Type	It can make the missile obtain a great initial velocity, which is very beneficial to quickly capture and hit the target	The missile and its instruments and equipment are subject to great impact and overload, which are only suitable for small anti-tank missiles with simple equipment
Hydraulic Type	Good rapidity, high power and high efficiency	The equipment is sophisticated, complex, has a hight rate of failure, and is difficult to maintain, and not suitable for field operations
Compressed-Air Type	Using high-pressure air as the power source, the missile can be ejected at a high speed without pollution	The pipeline system is complex, the equipment is bulky, and it is inconvenient for the army to use and maintain. It is difficult to make large-capacity and high-pressure gas cylinders[2]
Hydraulic-Pneumatic Type	Combination of hydraulic type and compressed-air type	The disadvantage is also the combination of hydraulic type and compressed-air type
Gas Type	High energy storage density, large ejection energy, small volume and simple equipment	The gas temperature is high (usually above 1500℃), which poses a threat to the missile equipment and launching facilities. The gas contains CO, H_2S, SO_X, etc. that can cause water pollution after being dissolved in water[3]
Gas-Steam Type	Adjustable energy, stable pressure change, ideal interior ballistic parameters	The device is more complicated than the gas type, the volume is also increased, the cost is increased, and the energy is “subtracted”. The gas contains CO, H_2S, SO_X etc., which will cause water pollution after being dissolved in water[4]
Electromagnetic Type	It has no noise, no light, no pollution, no erosion to guide rail and equipment, and can get great derailment speed after ejection	The equipment is large and complex, and super capacitors are difficult to break through. The strong electromagnetic field will affect the normal work of the missile equipment[5]

With the development of missile weapon system in the direction of function diversification, practical performance, platform integration, equipment serialization, environmental protection and pollution-free,

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it has become an urgent need for the innovative development of launch power technology to research and develop new principles and technologies that can replace solid propellant power technology, implement low-temperature and clean missile launch, improve the proportion of energy regulation, adapt to the complex environment of a large-scale combat area, reduce the support intensity in mobile combat, and achieve the goal of wide-range mobility, multi-purpose, low-cost, and maintenance free operations.

The liquid CO_2 phase transition ejection technology utilizes the characteristics of low-temperature phase transition, large gas production, and stable chemical properties of CO_2[6, 7], with the excitation of electric or gas, excites and injects the liquid CO_2 stored at high pressure into the space behind the missile to form CO_2 gas in a certain pressure to eject the missile out of the cylinder, which is a new launch principle of phase transition of forming ejection gas at room temperature or low temperature. Liquid CO_2 phase transition ejection technology breaks the disadvantages of compressed-air ejection, which are huge structure, difficult maintenance, propellant ejection gas ablation and pollution, and due to the low temperature and clean gas, it has outstanding advantages of high versatility, low launch cost, and environmental friendliness, and will open up a new research fields for the development of missile launching technology.

In this paper, by studying the characteristics of liquid CO_2 phase transition, a mathematical model of internal ballistics of liquid CO_2 phase transition ejection power system is established. Through simulation calculations, the internal ballistic parameters such as the pressure of launcher, missile velocity, missile acceleration and missile displacement are obtained, which are compared with the data obtained during the test under the same conditions to verify the effectiveness of the model; under the conditions of the missile tactical index (such as wide range variable depth launch, missile exit velocity, etc.), it provides certain help for the design of the ejection device.

2 Liquid CO2 Phase Transition Ejection Power System

2.1 Structure and Composition

The liquid CO_2 phase transition ejection power system is mainly composed of a liquid storage device and an excitation system, among which, the liquid CO_2 storage device is composed of a liquid CO_2 storage chamber, liquid CO_2, and a constant pressure rupture plate, and the excitation system is composed of excitation controller and excitation device. The structure diagram is shown in Fig. 1.

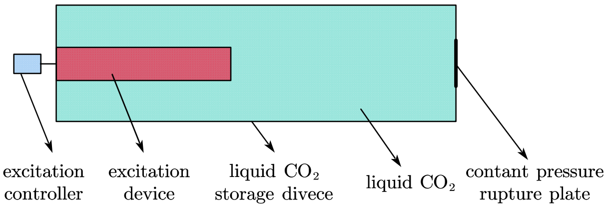

Fig. 1. Structure Diagram of Liquid CO_2 Phase transition Ejection Power System

2.2 Working Principle

Working principle of the liquid CO_2 phase transition ejection power system: when the launch command is received, the excitation controller quickly activates the excitation device to increase its temperature and release a large amount of heat. At this time, the normal temperature liqiud CO_2 in the liquid storage chamber absorbs heat and changes phase, and it instantly expands and gasifies, causing the pressure in the liquid storage chamber rises sharply. When the limit strength of the constant pressure rupture plate is reached, the high-pressure gas (with a small amount of liquid CO_2) break through the constant pressure rupture plate and enters the bottom of the launcher to build pressure. When the thrust at the bottom of the launcher is greater than the resistance of the launching load, the launching load starts to move and ejects out of the launcher. The work flow chart is shown in Fig. 2.

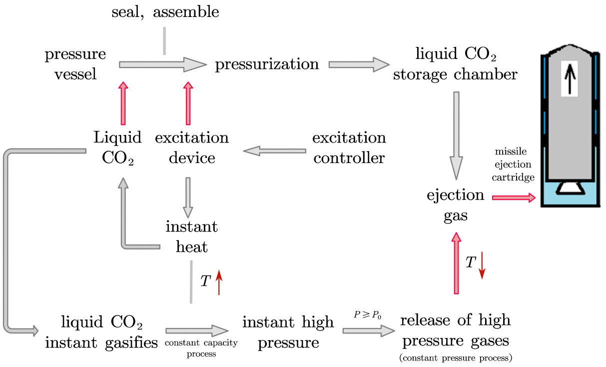

Fig. 2. Work Flow Chart of Liquid CO_2 Phase Transition Ejection Power System

3 Mathematical Model of Launch Interior Ballistics

3.1 Basic Assumptions

The actual launch process of the liquid CO_2 phase transition ejection power system is a very complex process of energy exchange and energy conversion. Starting from the main contradiction, assumptions made in the calculation model of liquid CO_2 phase transition ejection interior ballistics are as follows:

a) In the process of the liquid CO_2 in the liquid storage chamber being excited by the excitation device, the excitation coefficient is introduced to indicates the degree of excitation. is related to the quality of the liquid CO_2 and the heat released by the excitation device;

b) When the gaseous CO_2, liquid CO_2 and the air, which are continuously entering the launcher, can be uniformly mixed at every instant to exchange energy and form a mixture with uniform state parameters at each point, the CO_2 and air in the launcher are regarded as ideal gases;

c) Without considering the change of the parameters of the air flow along the pipeline, the flow of the working gas along the pipeline is regarded as the process of the transmission of the working medium energy from the launching power system to the launching cylinder.

d) The process of supercritical CO_2 entering the launch tube is very short, assuming that it is adiabatic flow and does not transfer heat with the environment;

e) For the process of supercritical CO_2 entering the launch tube will undergo phase transition, throttling and expansion, etc., the energy calculation is too complicated. This article assumes that the temperature of the working gas in the launcher is a certain value to simplify model;

f) The energy depreciation caused by irreversibility and the mass loss caused by air leakage are considered by pressure coefficient;

g) Consider the existence of macro kinetic energy of the working gas in the launcher by introducing the kinetic energy coefficient, and assume that its value is a constant throughout the launch process;

3.2 Equations of Launch Interior Ballistics

3.2.1 Energy Equation

When the phase transition ejection occurs, the excitation device in the liquid CO_2 phase transition chamber is activated, and a large amount of heat is generated instantaneously. Before the constant pressure shear plate breaks, a high temperature and high pressure environment is generated in the liquid CO_2 phase transition chamber, and its temperature is related to the input heat Q:

$$Q = \int_{T_1}^{T_2} c_v m_c \, dT \tag{1}$$

In the formula, Q—the heat released by the excitation device, J; c_v —the specific heat capacity of CO_2, $\mathrm{J/(kg \cdot K)}$; m_c —the mass of CO_2, kg; T —the temperature of CO_2 in supercritical state, K.

3.2.2 State Equation

Before the constant pressure shear plate ruptures, the pressure and temperature of CO_2 in the liquid storage chamber exceed the critical pressure and critical temperature. At this time, the liquid CO_2 undergoes a phase transition and turns into a supercritical state, and that is when it has the intermolecular force close to the gas state, so the equation of gas state is also applicable to the supercritical state. The equation of state of an ideal gas is only applicable when the gas pressure is not very high, which, under high pressure conditions, cannot express the properties of real gas[8]. To calculate the pressure change in the liquid CO_2 phase transition chamber, the equation of real gas state is needed. Since the CO_2 molecule is a non-polar molecule, the R-K-S equation can be used to do the calculation.

$$P_Z = \frac{RT_Z}{V_m - b} - \frac{a(T)}{V_m(V_m + b)} \tag{2}$$

$$a(T) = 0.43\frac{R^2 T_Z^2}{P_c}\alpha(T_r) \tag{3}$$

$$\alpha(T_r) = [1 + m(1 - T_r^{0.5})]^2 \tag{4}$$

$$b = 0.08664\frac{RT_c}{P_c} \tag{5}$$

$$T_r = \frac{T_Z}{T_c} \tag{6}$$

$$V_m = \frac{M}{\rho_z} \tag{7}$$

$$m = 0.48 + 1.574w - 0.176w^2 \tag{8}$$

After finishing the above, the equation of state supercritical CO_2 in the storage chamber is as follows:

$$P_Z = \frac{8.314 T_Z \rho_z}{0.044 - 3\times10^{-5}\rho_z} - \frac{0.372[1 + 0.825(1 - T_r^{0.5})]^2 \rho_z^2}{0.001936 + 1.32\times10^{-6}\rho_z} \tag{9}$$

$$\rho_z = \begin{cases} \dfrac{m_{c0}}{V_Z} & P_Z \leqslant P_P \\ \dfrac{m_{c0} - m_{ct}}{V_Z} & P_Z > P_P \end{cases} \tag{10}$$

In the formula, P_Z —fluid pressure in the liquid storage chamber, Pa; P_P —maximum pressure of the constant pressure rupture plate, Pa; T_Z —absolute temperature in the liquid storage chamber, K; V_Z —volume of the liquid storage chamber, $\mathrm{m^3}$; ρ_z—density of the fluid in the liquid storage chamber, $\mathrm{kg/m^3}$; m_{c0} —initial CO_2 mass in the liquid storage chamber, kg; m_{ct}—mass of the CO_2 flowing out of the liquid storage chamber, kg; V_m —Molar volume, $\mathrm{L/mol}$; R —gas constant, J/(mol·K); T_c —critical temperature, K; P_c —critical pressure, Pa; T_r —contrast temperature; w —eccentricity factor.

Based on the ideal gas assumption, apply the equation of ideal gas state to the CO_2 gas and air in the launch tube:

$$P_t = \frac{x_p(R_c m_{ct} + R_a m_a)T_t}{S_t(l_0 + l)} \tag{11}$$

In the formula, P_t —pressure in the launch cylinderl, Pa; x_p —pressure index, R_c and R_a —gas constants of CO_2 and air, J/(mol • K); T_t = t_t + 273.15, which is assumed as a fixed value, K; S_t—cross-sectional area of the launch tube, m^3; l_0—equivalent length of the initial volume at the bottom of the tube, m; l —movement displacement of the missile, m.

3.2.3 Flow Equation

When the fluid pressure of the supercritical CO_2 in the storage chamber is greater than the limit pressure of the constant pressure rapture plate, the plate ruptures, and the liquid CO_2 that is not excited in the storage chamber will enter the launcher along with the supercritical CO_2. This process can be approximately regarded as adiabatic flow process. The amount of CO_2 flowing into the launcher from the constant pressure rupture plate in the liquid storage chamber is calculated according to the following formula:

$$m_{ct}=\int_0^t \alpha\rho_c A v_c dt \tag{12}$$

$$v_c=\sqrt{\frac{2k}{k-1}R_cT_Z\left[1-\left(\frac{P_t}{P_Z}\right)^{\frac{k-1}{k}}\right]} \tag{13}$$

$$\rho_c=\rho_z\left(\frac{P_t}{P_Z}\right)^{\frac{1}{k}} \tag{14}$$

In the formula, A—the cross-sectional area of the outlet of the constant pressure rupture plate, m^2; ρ_c—the density of the fluid at the outlet of the constant pressure rupture plate, $\mathrm{kg/m}^3$; v_c—the fluid velocity at the outlet of the constant pressure rupture plate, $\mathrm{m/s}$.

3.2.4 Equation of Missile Motion

The motion equation of the missile under the action of the working gas satisfies the following formula:

$$Ma=(1+x_k)P_tS_t-F \tag{15}$$

In the formula, Ma is the total external force experienced by the missile in the launcher, a is the missile acceleration, and x_k is the kinetic energy coefficient.

The range and velocity of missile motion are calculated by common taylor series:

$$l_n=l_{n-1}+\Delta t\cdot v_{n-1}+\frac{1}{2}\Delta t^2a_{n-1}+\frac{1}{6}\Delta t^3\dot{a}_{n-1} \tag{16}$$

$$v_n=v_{n-1}+\Delta t\cdot a_{n-1}+\frac{1}{2}\Delta t^2\dot{a}_{n-1} \tag{17}$$

$$\dot{a}=\frac{a_n-a_{n-1}}{\Delta t} \tag{18}$$

The motion resistance of the missile is: $F=(1+Z)Mg+P_0S_t$;

In the formula, $Z=F_Z/(M\times g)$—friction coefficient of missile loading, F_z—friction of missile loading, P_0 is the atmospheric pressure.

The above equations together constitute the liquid CO_2 phase change ballistic model, which can calculate the pressure of the working gas in the launcher, the velocity, acceleration and the rule of the displacement of the missile during the launch process.

3.3 Result Analysis

Based on the mathematical model of the launch interior ballistics of the liquid CO_2 phase transition ejection device established by the above analysis, the simulation calculation program is compiled, among which, the initial parameters such as the mass of liquid CO_2 and the weight of the missile are consistent with the test values. The launch parameters such as the pressure in the launcher and the velocity and acceleration of the missile motion are obtained by simulation calculation, and compared with the launch parameters measured in the test process, as shown in the figure below. All data in this paper are normalized.

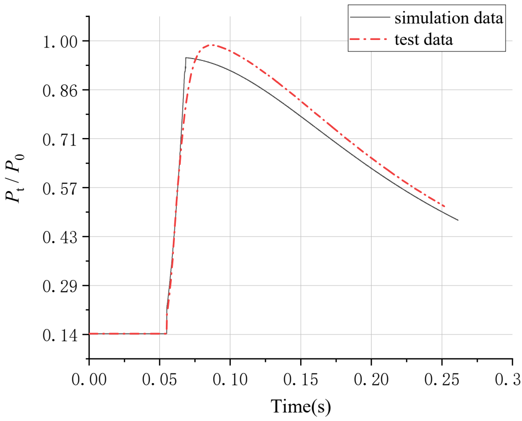

Fig. 3. Comparison Chart of the Pressure-Time Curve

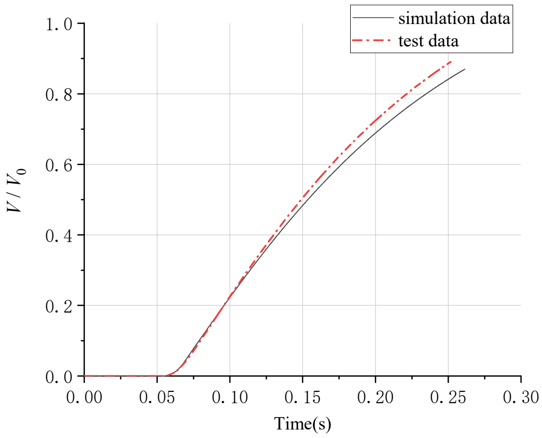

Fig. 4. Comparison Chart of the Velocity-Time Curve

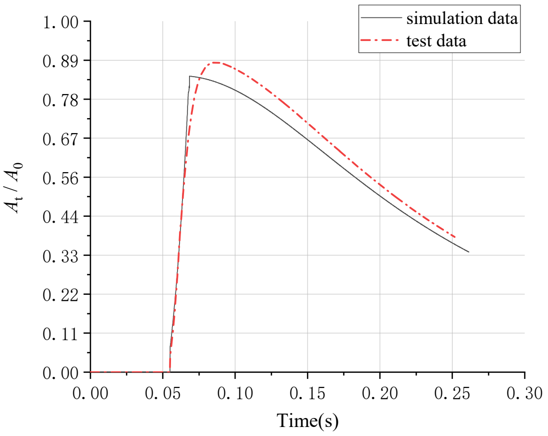

Fig. 5. Comparison Chart of the Accelearation-Time Curve

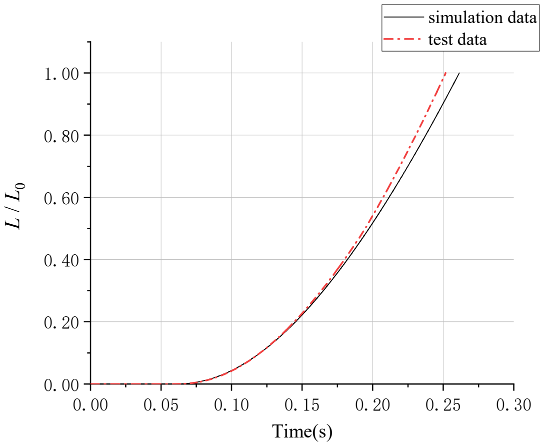

Fig. 6. Comparison Chart of the Displacement-Time Curve

As shown in the figure above, when the liquid CO_2 phase transition ejection device launches a missile, the launch internal ballistic curve of velocity, acceleration, pressure, etc. are stable, which verifies the feasibility of the liquid CO_2 phase transition ejection technology; The maximum acceleration in the missile barrel is close to 16g before normalization, which may cause safety hazards such as debonding of the engine charge in the missile. Next, the working time of the liquid CO_2 phase change ejection power system can be extended by reducing the outlet throat diameter of the liquid CO_2 reservoir or using a multi-liquid CO_2 phase change ejection module to achieve the purpose of reducing the acceleration in the missile barrel. By comparing the simulation results of the mathematical model of the liquid CO_2 phase transition ejection device launch interior ballistic with the test data, it can be seen that the pressure in the launch barrel and the velocity, acceleration, and missile displacement of the missile movement obtained by the simulation calculation are in good consistency with the test result, thus verify the validity of the mathematical model of launch interior ballistics of CO_2 phase transition ejection device established in this paper.

4 Conclusion

Liquid CO_2 phase transition ejection technology breaks the disadvantages of compressed-air ejection, which are huge structure, difficult maintenance, propellant ejection gas ablation and pollution, and it has outstanding advantages of high versatility, low launch cost, and envrionmental friendliness, etc. In this paper, a mathematical model of internal ballistics of the liquid CO_2 phase transition ejjtion power system is established under a certain assumptions. And through simulation calculation, the launching parameters such as the pressure in the launcher, the velocity and acceleration of the missile are obtained, and they is compared with the test data to verify the validity of the model. Further, under the conditions of the missile tactical index (such as wide range variable depth launch, missile exit velocity, etc.), it provides certain help for the design of the liquid CO_2 phase transition ejection device.

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