

Article

Study on the Growth and Desorption of Lubricating Oil Droplets in Space Under Piezoelectric Drive

Zhaoliang Dou ^{1,*}, Jianfang Da ¹, Gang Zhou ², Shaohua Zhang ², Wenbin Chen ¹ , Ye Yang ¹, Hongjuan Yan ¹ and Fengbin Liu ¹

¹ School of Mechanical and Materials Engineering, North China University of Technology, Beijing 100043, China; 15834392031@163.com (J.D.); chenwenbin@ncut.edu.cn (W.C.); yangye@ncut.edu.cn (Y.Y.); yanhj@ncut.edu.cn (H.Y.); fblu@ncut.edu.cn (F.L.)

² Beijing Key Laboratory of Long Life Technology for Precision Rotation and Transmission Mechanisms, Beijing Institute of Control Engineering, Beijing 100094, China; zhougang502@126.com (G.Z.); 18810227082@139.com (S.Z.)

* Correspondence: dzl@ncut.edu.cn

Abstract

Aiming at satisfying the micro-dynamic lubrication requirements of moving parts in spacecraft on-orbit operation, this paper proposes a micro-oil supply scheme based on a piezoelectric drive. The working mode and transient sound pressure characteristics of the micro-oil supply device were analyzed by the numerical simulation method, and the influence of driving voltage and oil dynamic viscosity on droplet growth and desorption behavior was investigated. The research results show the following: (1) The driving voltage is a key external control parameter that affects the droplet ejection characteristics. The increase of its amplitude will promote the droplet morphology to change from a stable and concentrated overall state to a dispersed state with multi-satellite droplets and easy necking fracture. At the same time, the droplet size is significantly reduced, the distribution tends to be discretized and the droplet velocity and droplet mass are simultaneously improved. Under the 220 V voltage condition, the droplet ejection velocity can reach 17.8 m/s, and the single ejection mass can reach 6.98 mg, which can realize the rapid and large-scale delivery of droplets. (2) Dynamic viscosity is the core intrinsic parameter to determine the droplet ejection characteristics. When the value of dynamic viscosity increases, the droplet morphology will change from the wire-like fracture characteristics of ‘spherical head + satellite droplet developed’ to the droplet-like structure with overall concentration and stable mechanical state. The average droplet size increased and the distribution was more aggregated. The droplet velocity and droplet mass decreased significantly. When the viscosity increased to 0.16 Pa·s, the droplet ejection velocity decreased to 1.14 m/s, and the single ejection mass decreased to 0.35 mg.

Keywords: piezoelectric drive; droplets; growth; desorption



Received: 24 January 2026

Revised: 21 February 2026

Accepted: 26 February 2026

Published: 3 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

In aerospace missions, the reliability of moving parts determines key factors for the successful completion of the mission. Excellent lubrication performance, low friction coefficient and low wear rate are the core foundation to ensure its stable operation within the design life [1]. In the study of lubrication and friction and wear between relatively moving surfaces in space environment, space tribology is an important theoretical and experimental basis. It often involves complex working conditions including vacuum, weight loss, large

temperature range, etc., and has strong engineering application practicality and complexity [2,3]. Although space tribology has been developed for many years, it is still difficult to match the increasing performance requirements of spacecraft in terms of reliability and life indicators of mechanical moving parts [4]. The spacecraft moving parts generate heat due to friction during on-orbit operation. Because it is difficult to effectively dissipate heat within the environment of space, it is easy to cause failure problems such as lubricating oil volatilization and lubricating film rupture. The above situation will significantly weaken the lubrication effect and force the moving parts to operate under poor lubrication conditions for a long time [5]. Lubrication failure can cause excessive friction and wear, threatening the stability of spacecraft in orbit, which is the main cause of attitude control system failure [6]. This poses a greater challenge to space lubrication technology. The current technical system includes two major branches: passive and active. Passive lubrication uses centrifugation or surface migration as the driving force for oil supply. Typical implementation methods include centrifugal lubrication [7], exudation lubrication [8], oil rope lubrication [9] and porous medium lubrication [10–12]. The amount, time and position of passive lubrication cannot be adjusted according to real-time working conditions, and it is difficult to respond to the dynamic changes of load and wear. It is easy to cause improper oil supply or timing deviation, and the adaptability of working conditions is significantly insufficient. It is the basic feature of active lubrication to supply oil according to the instructions of the control unit. Its typical technical path covers static oil storage [13], electromagnetic drive [14] and piezoelectric drive lubrication [15]. Among them, the precision control of single oil supply is the key restricting its development. Excessive oil supply will make the bearing friction torque increase nonlinearly, resulting in increased friction energy consumption and abnormal wear of moving parts, which will ultimately affect the service life of the spacecraft. Therefore, the development of new lubrication technologies that can achieve timely, trace and accurate replenishment of lubricating oil has become the key to breaking through the bottleneck of long-term service of spacecraft.

In the field of micro-oil supply, piezoelectric drive technology based on the inverse piezoelectric effect has attracted much attention due to its high precision, fast response, anti-interference and self-locking characteristics [16,17]. At present, the related research at home and abroad has made great progress, which provides a new idea for space active lubrication technology. In terms of piezoelectric drive structure, Huang et al. [18] found through experiments that stacked piezoelectric transducers can obtain higher power output by parallel connection under the same load. Yang et al. [19] designed a piezoelectric driven diaphragm micro air pump, and the test showed that the output flow rate reached 192 mL/min under 50 V resonant drive. In terms of fuel supply performance, its flow coverage has been extended from micro-upgrade to milliliter upgrade to meet the needs of different scenarios. For the micro-lubrication scenario, Li et al. [20] developed a piezoelectric micro-jet device with a single oil supply of as low as 6×10^{-6} mL. For large flow requirements, the piezoelectric ultrasonic atomizer developed by Axel Lefebure and Dongha Shim [21] can achieve continuous atomization output of 13.4 mL/h. In addition, the screw-type piezoelectric actuator designed by Sun Jianhua et al. [22] completed the oil supply control of a single pulse of 6×10^{-5} mL. In terms of droplet detachment behavior, German et al. [23] explored the formation and separation process of droplets at the capillary tube for Newtonian fluids, shear-thinning fluids and viscoelastic fluids. It was found that the type of fluid and yield stress affect the filament diameter, necking characteristics and shedding time of droplets. Through numerical simulation, Liu [24] revealed the dynamic process of droplet formation at the end of a low-flow capillary, and clarified the three-stage evolution law of its formation, necking and fracture. Experiments show that the increase of droplet viscosity will prolong the necking line. The VOF numerical simulation results of

Yang et al. [25] show that increasing the inner diameter of the microtube can increase the falling speed, average diameter and necking line length of the sodium alginate solution.

Piezoelectric drive micro-oil supply technology has important application value in the field of ultra-precision lubrication of spacecraft. However, there are still two key problems in the existing research for this special working condition. On the one hand, the key components of spacecraft need to achieve ultra-micro and high-precision lubrication, but there is a significant gap between the single oil supply of the existing oil supply device and it. On the other hand, the inherent law between the controllability and stability of droplet desorption behavior and oil supply is still unclear, which hinders the optimization and breakthrough of oil supply accuracy. Aiming at the problems of insufficient micro-output capacity and limited dynamic control accuracy of current piezoelectric oil supply technology, especially the lack of in-depth understanding of the internal coupling mechanism among ‘piezoelectric vibration-flow field response-droplet forming’, this paper designs a piezoelectric drive oil supply device with a single conical hole structure metal sheet as the core, and systematically analyzes its oil supply characteristics. The main research contents are as follows:

- (1) A piezoelectric driving structure with a piezoelectric ceramic ring and a metal sheet with a cone hole as the core is constructed. Under the action of vibration excitation, the throttling effect formed by section shrinkage is used to realize the precise control of flow rate when oil flows through the cone hole, which provides a reliable guarantee for the stable realization of micro-oil supply from the structural design level.
- (2) Based on the numerical simulation method, the dynamic analysis of the piezoelectric vibrator is carried out. Firstly, its working mode and natural frequency are defined by modal analysis. Then, the transient analysis is carried out to obtain the sound pressure curve generated by the structural vibration. Finally, the sound pressure curve is used as the pressure inlet boundary condition of two-phase flow simulation to realize the coupling simulation of structural vibration and fluid response.
- (3) The VOF two-phase flow model is used to simulate the droplet ejection characteristics. The influence mechanism of key parameters such as excitation voltage and oil dynamic viscosity on the dynamic process and periodic evolution law of droplet desorption is mainly explored, and then the internal correlation logic of ‘piezoelectric vibration-flow field response-droplet forming’ is revealed, which provides core theoretical support for the precise control of the micro-oil supply process.

2. Materials and Methods

2.1. Working Principle and Structure

(1) Working Principle

(1) Jet drive mechanism: The inverse piezoelectric effect makes the piezoelectric ceramic sheet produce axial vibration in an alternating electric field, which leads to the periodic change of the liquid cavity volume [26]. In the high-level stage, the piezoelectric plate stretches and compresses the liquid chamber, and the pressure in the chamber rises above the surface tension threshold, which induces the droplet to squeeze out from the nozzle. In the low-level stage, the contraction of the piezoelectric plate expands the liquid chamber, and the pressure in the chamber is reduced or even negative pressure is generated, causing the fluid to reverse filling. At this time, the droplets that have been separated from the nozzle continue to move with inertia, completing the separation from the fuel supply body and achieving a single pulse injection, as illustrated in Figure 1.

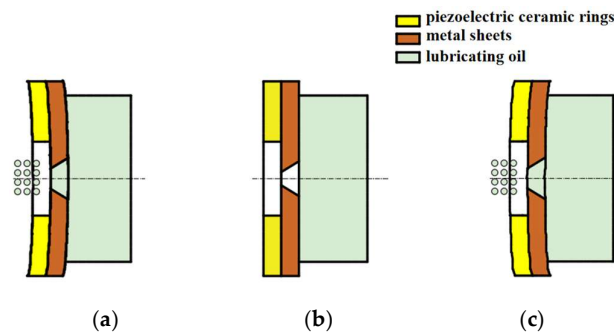


Figure 1. Schematic diagram of piezoelectric oscillator vibration principle. (a) High level excitation; (b) No pulse excitation; (c) Low level excitation.

(2) Pressure storage and supply mechanism: pressure reserve and release are realized by means of spring–piston system. In the compression stage, the external load makes the spring store elastic potential energy; in the energy release stage, the spring-driven piston moves smoothly along the preset trajectory. The mechanism can effectively inhibit the generation of bubbles in the oil supply path, ensure the smooth and reliable movement of the piston, maintain the uniform contact state between the lubricating oil and the large end face of the cone hole and provide a pressure guarantee for continuous and stable injection.

(2) Structure

In view of the narrow space and complex structure of the spacecraft, the active micro-oil supply device must have a small volume, light weight and compact structure. The piezoelectric micro-oil supply device is composed of a drive module, pressure storage module, oil storage module, shell and end cover. The driving unit adopts the piezoelectric ceramic ring formed by tape casting and the metal sheet processed by laser precision machining to complete the driving output and amplitude amplification, respectively. The pressure storage unit is composed of a spring, piston and mounting seat, which mainly undertakes the function of pressure storage. The shell and the end cover integrate and encapsulate each component, the snap ring and the sealing ring to form a compact and fully functional oil supply device, as shown in Figure 2.

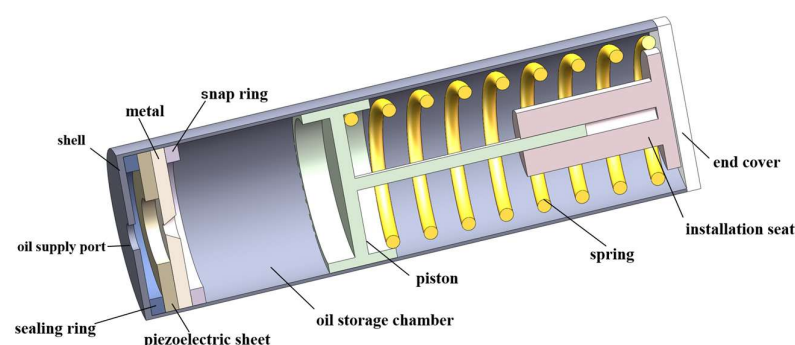


Figure 2. Schematic diagram of the structure of piezoelectric micro fuel supply device.

2.2. Finite Element Model of Piezoelectric Oscillator

2.2.1. Theory and Control Equations

(1) Piezoelectric constitutive equations

The core physical basis of the piezoelectric micro-oil supply device is the piezoelectric effect, and the electromechanical coupling characteristics of piezoelectric materials can be accurately described by the piezoelectric constitutive equation. The stress T and electric

field strength E are used as independent variables, and the strain S and electric displacement D are used as the corresponding dependent variables:

$$\begin{cases} S = s^E T + d^t E \\ D = d T + \epsilon^T E \end{cases} \quad (1)$$

where S is the strain tensor; T is the stress tensor; D is the electric displacement vector; E is the electric field intensity vector; s^E is the elastic flexibility matrix under constant electric field; d is the piezoelectric constant matrix; d^t is the piezoelectric constant matrix and its transpose; ϵ^T is the dielectric constant matrix under constant stress.

The corresponding effects of different vibration modes are different. The PZT-5H piezoelectric ceramic sheet used in this paper takes the stretching vibration in the thickness direction as the main vibration mode. This equation provides the core theoretical support for the establishment of a finite element model and the analysis of electromechanical coupling transient sound pressure characteristics.

(2) Vibration equation of piezoelectric vibrator

The control equation derived based on the Hamiltonian principle can be used to describe the dynamic behavior of the piezoelectric vibrator in this paper. The weak form integral expression is as follows:

$$\int_V (\rho \delta u^T \ddot{u} + \delta S^T T - \delta E^T D) dV = \int_S \delta u^T t dS \quad (2)$$

where ρ is the material density; u is the displacement vector; δ is the variational symbol; t is the surface force vector.

The target application of this study is a low-earth-orbit satellite, and its typical operating temperature range is 0~40 °C. The numerical simulation in this paper is carried out at room temperature (about 25 °C), which is located in the above on-orbit temperature range. In this temperature range, the material parameters of the space-grade piezoelectric ceramics change little, so the linear constitutive relation used in Equation (2) has sufficient accuracy.

By finite element discretization of the above expression (2), the following matrix equations can be derived:

$$\begin{bmatrix} M & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \ddot{U} \\ \ddot{\Phi} \end{bmatrix} + \begin{bmatrix} C & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{U} \\ \dot{\Phi} \end{bmatrix} + \begin{bmatrix} K_{uu} & K_{u\phi} \\ K_{u\phi}^T & K_{\phi\phi} \end{bmatrix} \begin{bmatrix} U \\ \Phi \end{bmatrix} = \begin{bmatrix} F \\ Q \end{bmatrix} \quad (3)$$

where M is the mass matrix; C is the damping matrix; K_{uu} is the elastic stiffness matrix; $K_{u\phi}$ is the piezoelectric coupling matrix; $K_{\phi\phi}$ is the dielectric stiffness matrix; U is the node displacement vector; Φ is the node potential vector; F is the mechanical load vector; Q is the charge load vector.

(3) Damping model

Considering the significant influence of vibration energy dissipation on the sound pressure field, in order to accurately characterize the co-amplitude value and transient attenuation characteristics of the piezoelectric vibrator, the damping term needs to be introduced into the numerical model. In this paper, the Rayleigh damping model is used in the analysis of transient sound pressure characteristics in Section 3.2 to improve the accuracy of the analysis.

$$C = \alpha M + \beta K \quad (4)$$

where C is the damping matrix; M is the mass matrix; K is the stiffness matrix; α is the mass damping coefficient, $\alpha \approx 0$; β is the stiffness damping coefficient, $\beta \approx 6.48 \times 10^{-7}$ s.

2.2.2. Model and Settings

In this paper, the piezoelectric vibrator adopts the composite structure of a piezoelectric ceramic sheet and metal sheet, and the two are bonded by epoxy resin to ensure conductivity. Because the thickness of the bonding layer is much smaller than that of the matrix material, its influence on the sound pressure characteristics can be ignored, so the interface is set as an ideal connection in the simulation. The three-dimensional model of the vibrator based on Solidworks is shown in Figure 3, and the related material properties and geometric parameters are listed in Table 1.

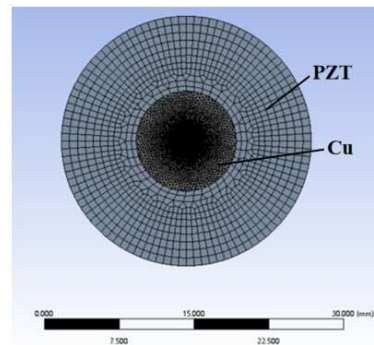


Figure 3. Schematic diagram of piezoelectric oscillator model.

Table 1. Parameters of piezoelectric oscillator.

	Inside Diameter (mm)	Outside Diameter (mm)	Thickness (mm)	Density (kg/m ³)	Elastic Modulus (N/m ²)	Pr
PZT5-H	10	25	0.2	7.45×10^3	7.65×10^{10}	0.32
Cu	--	25	0.2	8.3×10^3	1.33×10^{11}	0.35

The stiffness matrix, piezoelectric matrix and dielectric constant matrix of the piezoelectric ceramic plate are as follows:

$$\text{stiffness matrix } [c] = \begin{bmatrix} 13.2 & 7.3 & 7.1 & 0 & 0 & 0 \\ 7.3 & 13.2 & 7.1 & 0 & 0 & 0 \\ 7.1 & 7.1 & 11.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 \end{bmatrix} \times 10^{10} (\text{N/m}^2)$$

$$\text{piezoelectric matrix } [e] = \begin{bmatrix} 0 & 0 & -2.4 \\ 0 & 0 & -2.4 \\ 0 & 0 & 17.3 \\ 0 & 0 & 0 \\ 0 & 12.95 & 0 \\ 12.95 & 0 & 0 \end{bmatrix} (\text{C/m}^2)$$

$$\text{dielectric constant matrix } [e] = \begin{bmatrix} 804.6 & 0 & 0 \\ 0 & 804.6 & 0 \\ 0 & 0 & 659.7 \end{bmatrix}$$

In the ANSYS 2022 R1 simulation platform, the specific parameters are set as follows:

- (1) Piezoelectric material setting: The polarization direction of the piezoelectric ceramic sheet is set to the thickness direction, and the corresponding piezoelectric physical parameters are configured to accurately describe the electric field–displacement–stress multi-physical

field coupling relationship, so as to ensure that the reduction degree of the piezoelectric driving effect in the simulation is consistent with the actual physical law.

- (2) Boundary constraint application: The ring edge of the piezoelectric vibrator is constrained by a fixed support, and the rigid fixed boundary between the piezoelectric vibrator and the shell in the device is simulated. This boundary condition eliminates the influence of rigid body displacement on the calculation results and improves the agreement between the simulation model and the actual working conditions.
- (3) Mesh generation parameters: The model is discretized with tetrahedral elements. The upper limit of the global element size is 0.8 mm. The model contains 763,432 nodes and 453,915 elements. The grid independence verification shows that the change of key simulation results after further refinement of the grid is less than 2%, which proves that the current grid setting has sufficient accuracy and can provide reliable guarantee for subsequent simulation analysis.

2.3. Two Phase Flow Model

2.3.1. Theory and Control Equations

The motion behavior of the fluid is dominated by the three laws of mass conservation, momentum conservation and energy conservation. These three sets of equations together constitute the theoretical basis of computational fluid dynamics. According to the two-dimensional nozzle model established in this paper, the fluid is assumed to be incompressible, that is, is a constant. Based on the above conditions, the basic control equations applied to the analysis of gas–liquid two-phase flow in a two-dimensional flow field are finally established. It should be noted that the target application of this study is a low-earth-orbit satellite, and its typical on-orbit operating temperature range is 0–40 °C. The numerical simulation in this paper is carried out at room temperature (about 25 °C), which is located in the above on-orbit temperature range. In this temperature range, the lubricant remains liquid, and the continuous medium hypothesis is established. Therefore, the control equation adopted in this paper is applicable in this application scenario.

- (1) Conservation of mass equation

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} = 0 \quad (5)$$

where u_k is the velocity component in the k direction.

- (2) Energy conservation equation

$$\frac{\partial(\rho u_x)}{\partial t} + u_x \frac{\partial(\rho u_x)}{\partial x} + u_y \frac{\partial(\rho u_x)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + F_x \quad (6)$$

$$\frac{\partial(\rho u_y)}{\partial t} + u_x \frac{\partial(\rho u_y)}{\partial x} + u_y \frac{\partial(\rho u_y)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + F_y \quad (7)$$

where τ_{xx} , τ_{xy} and τ_{yy} are the components of the viscous stress τ acting on the surface of the microelements; p is the pressure exerted on the microelements; F_k is the resultant force acting on the microelements in the k direction.

- (3) VOF model

The VOF method is based on the fluid volume ratio function in the grid unit to realize the dynamic tracking of the gas–liquid interface and the reconstruction of the free surface. The model represents the phase fraction of the fluid by defining the variable α .

The phase scores are as follows:

$$\begin{cases} \alpha = 0, & \text{gas} \\ \alpha = 1, & \text{liquid} \\ 0 < \alpha < 1, & \text{gas - liquid interface} \end{cases} \quad (8)$$

The volume fraction equation is as follows:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha u) = 0 \quad (9)$$

where α is the phase fraction parameter; u is the common velocity vector of two fluids in the entire watershed; t is time.

In this study, the numerical simulation is carried out based on the k - ω Shear Stress Transport (SST) turbulence model. The model combines the accurate description ability of the k - ω model to the near-wall flow and the adaptability of the k - ε model to the free flow field. It can accurately describe the flow behavior under the inverse pressure gradient, and is suitable for the simulation analysis of the micro-nozzle droplet ejection process.

2.3.2. Model and Settings

The interior of the spacecraft is not an absolute vacuum, but maintains a specific low-pressure condition. This environmental characteristic determines that the coupling effect of gas–liquid two-phase flow must be taken into account when studying the liquid injection mechanism of a piezoelectric micro-jet device for space lubrication. In this paper, based on the theory of multiphase flow dynamics, the volume of fluid (VOF) numerical method in Fluent software (ANSYS 2022 R1) is used to simulate the injection behavior of lubricating oil in piezoelectric drive mode. The constructed gas–liquid two-phase flow model includes the internal flow area of the nozzle and the movement area of the external gas domain after the droplet is ejected. The finite element model and boundary conditions of the nozzle are shown in Figure 4, and the material properties and size parameters are shown in Table 2.

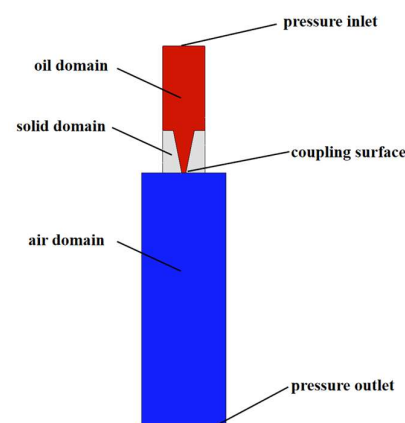


Figure 4. Two-phase flow model of droplet jetting.

Table 2. Physical parameters of gas–liquid two-phase materials.

	Dynamic Viscosity (Pa·s)	Density (kg/m ³)	Surface Tension (N/m)
Pao2	0.005	835	0.028
air	1.7894×10^{-5}	1.225	--

In the ANSYS simulation platform, the relevant parameters are set as follows:

- (1) Definition of physical properties of materials: The parameters of physical properties of materials involved in this model are summarized in Table 2. The air density is calculated based on the ideal gas model. The surface tension of oil–air phase and the contact angle of oil–air–metal wall are the key parameters to control the gas–liquid two-phase flow behavior.
- (2) Application of boundary conditions: The contact angle of the semi-hydrophilic nozzle solid wall is defined as 90° , the contact angle of the hydrophobic gas–liquid interface is defined as 175° , and the rest of the wall is no-slip. The global gravity acceleration is set to 0 m/s^2 to simulate the space microgravity environment. The pressure inlet boundary drives the flow by importing transient sound pressure data to ensure that the dynamic simulation of the injection process is consistent with the actual working conditions.
- (3) Mesh generation settings: The global maximum unit size is set to $1 \mu\text{m}$, generating 603,306 nodes and 600,455 units. The grid independence study shows that the change of key simulation results after further refinement of the grid is less than 2%, which proves that the current setting can ensure the calculation accuracy and lay the foundation for the reliability of subsequent simulation analysis.

3. Results and Discussion

3.1. Modal Analysis

With the help of ANSYS software, the modal parameters of the annular vibrator in a vacuum environment are solved based on the finite element model of the piezoelectric vibrator. The first four natural frequencies and vibration modes are shown in Table 3 and Figure 5, respectively, which lays a foundation for the subsequent dynamic response analysis.

Table 3. Vibration mode analysis results of piezoelectric vibrator.

Order	1	2	3	4	5	6	7	8	9	10
Frequency (Hz)	4914.2	8699.5	8702.1	15,013	15,065	15,428	23,020	23,078	24,209	24,229

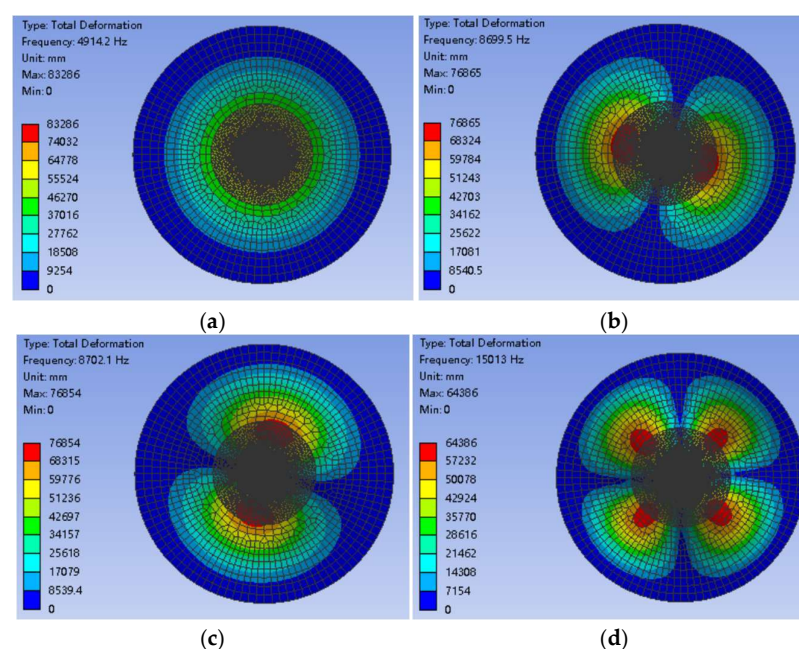


Figure 5. Modal analysis of piezoelectric oscillator. (a) First order; (b) second order; (c) third order; (d) fourth order.

Figure 5a is the first-order mode shape of the piezoelectric vibrator. The resonance frequency is 4914.2 Hz. The gradient sound pressure distribution with strong center and weak edge can guide the sound energy to converge to the center, so that the sound pressure amplitude in the central region is significantly improved. On the same radius circumference, the sound pressure phase of each point is consistent and the amplitude is equal, forming an axisymmetric stable sound field structure. When the oscillator moves upward, a positive pressure environment is formed in the surrounding space, and the device completes the oil absorption. When moving downward, the space turns into negative pressure, and the device enters the fuel injection stage. The periodic change of positive and negative pressure alternately provides an ideal sound field environment for the stable injection of droplets.

Figure 5b,c are the second-order and third-order modal shapes of the piezoelectric vibrator, and the resonance frequencies are 8699.5 Hz and 8702.1 Hz, respectively. Two axisymmetric sound pressure regions appear on the surface of the oscillator. At the same moment, the sound pressure phases of the two regions are opposite, and the influence range does not involve the center of the oscillator. This feature leads to the weak energy of the axial sound pressure wave, which has difficulty forming the effective sound pressure gradient required to drive the droplet ejection, which is not conducive to the normal generation and desorption of the droplet.

Figure 5d is the fourth-order modal shape of the piezoelectric vibrator. The resonant frequency is 15,013 Hz, and four independent sound pressure change areas are distributed on the surface of the vibrator. The coverage of each region is small, the sound pressure fluctuation is gentle and the amplitude is the lowest in the fourth order. At the same time, the phase of the four regions at the same time is different, and the sound pressure effect also does not extend to the central region, resulting in insufficient axial sound energy accumulation, which cannot provide enough sound pressure driving force to drive the droplet ejection.

In summary, the first-order mode has significant advantages in a vacuum environment: the sound pressure field is symmetrically distributed, the sound energy is efficiently focused on the central region and the dynamic change law is stable, which provides a favorable support for the stability and controllability of droplet ejection. The core advantages of the first-order mode compared to the higher-order modes are mainly manifested in the following two points: First, it is easy to establish a clear quantitative relationship between the sound pressure response and the driving signal, which lays a foundation for the precise control of the injection process; secondly, the structure of the sound pressure field is simple, and the low-order characteristics reduce the stringent requirements for structural machining accuracy and assembly process, which is helpful to suppress the abnormal fluctuation of sound pressure caused by manufacturing errors. Therefore, this study selects the first-order mode as the working mode of the piezoelectric vibrator.

3.2. Transient Sound Pressure Characteristics Analysis

To investigate the sound pressure characteristics and central particle vibration laws of piezoelectric oscillators, this study used a 4914.2 Hz sine wave as the excitation signal and applied continuous pulse voltages of 24 V, 48 V, 55 V, 110 V and 220 V with five different amplitudes to the piezoelectric oscillator. The research focuses on the regulation effect of excitation voltage on sound pressure. The measured sound pressure data will be used as the pressure inlet boundary condition and included in the subsequent analysis process. At the same time, the system compared the dynamic changes of sound pressure parameters and vibration period of the central particle of the piezoelectric oscillator with the excitation voltage.

As shown in Figure 6, the sound pressure output exhibits significant transient characteristics, which are independent of the driving voltage and belong to the inherent dynamic

response of the system. Taking the measured precise data under 24 V voltage as a typical case: the first three pulses correspond to the energy accumulation and rapid vibration stage, and the sound pressure amplitude sharply rises from 0.0095 MPa to a peak of 0.0239 MPa. This phenomenon indicates that the system requires approximately 460 μ s of energy accumulation time to reach maximum response from a stationary state, confirming the inertial effect generated by the coupling of piezoelectric oscillators and fluid mass. After the peak, the sound pressure enters the attenuation stage, where it continues to decay under the damping effect of the system (mainly fluid viscosity dissipation and sound radiation). The pulse evolution pattern of “rising first and then falling” remains consistent under all test voltages, reflecting that the energy injection, storage, and dissipation processes of the system follow a unified physical mechanism.

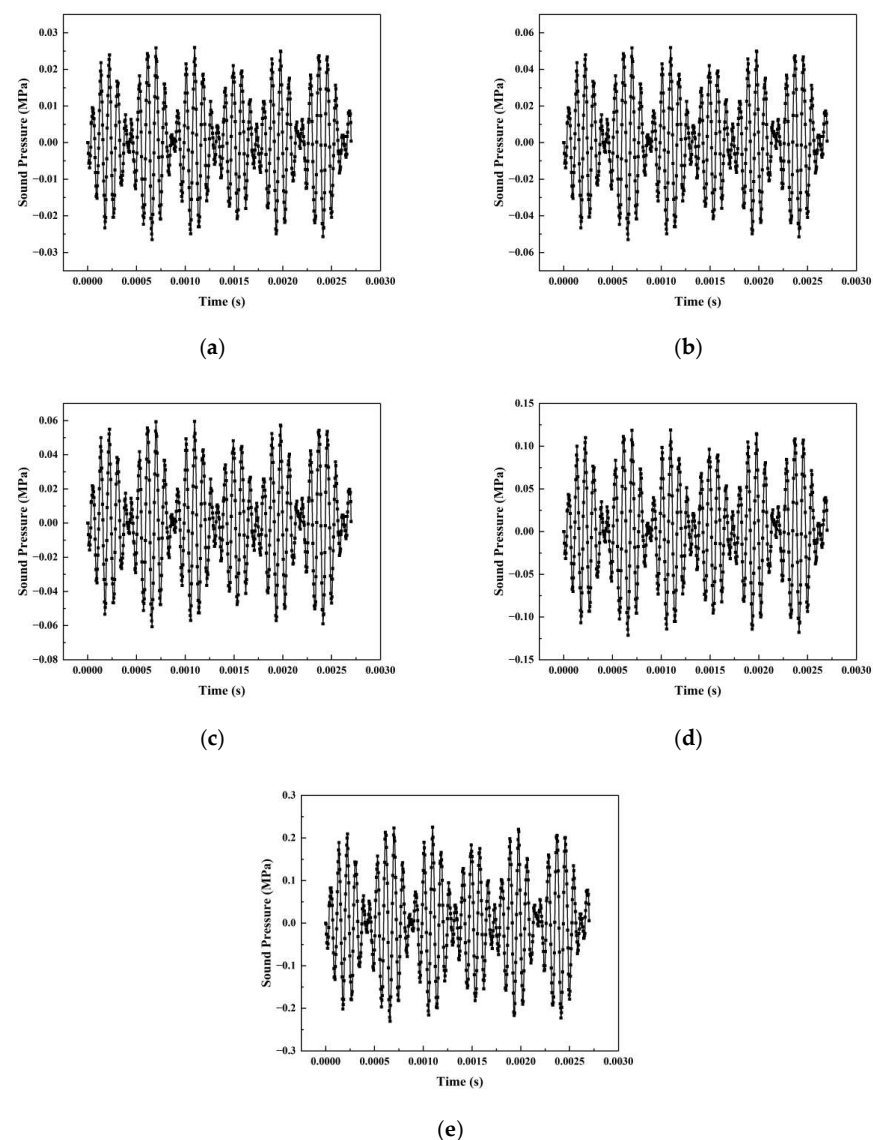


Figure 6. The relationship curve of particle sound pressure with time under different voltage amplitudes. (a) 24 v; (b) 48 v; (c) 55 v; (d) 110 v; (e) 220 v.

Further analysis reveals that although the transient waveform is consistent, its peak value exhibits a highly linear proportional relationship with the driving voltage, meaning that the higher the voltage, the greater the peak sound pressure. This result indicates that within the voltage range set in this study, the inverse piezoelectric effect of the piezoelectric oscillator always operates in a linear state, ensuring the high efficiency and predictability

of electro acoustic energy conversion. This feature provides a key technical path for precise control of jet driving force: by quantitatively adjusting the driving voltage, linear matching of sound pressure intensity can be achieved, thereby regulating the growth and desorption process of droplets, achieving precise control of fuel supply quantity and speed.

3.3. Visualization of Dynamic Characteristics of Oil Growth and Desorption

To further explore the intrinsic mechanism of droplet generation under piezoelectric driving, this study selected a typical operating condition of 55 V driving voltage and adopted a high spatiotemporal resolution numerical simulation method to finely capture and analyze the complete process of droplet growth and desorption from the nozzle outlet. The total simulation duration is 340 μs , covering four consecutive excitation cycles. The initial cycle is 100 μs , and the three subsequent cycles are all 80 μs . Within each cycle, the complete lifecycle of a single droplet can be clearly observed, including formation, stretching and detachment processes, accompanied by significant interface morphology evolution and dynamic reconstruction of the interface.

It can be seen from Figure 7 that the droplet evolution has significant periodic characteristics and good repeatability. During the first cycle (0–100 μs), the droplet completes initial nucleation, volume convergence, and first desorption at the nozzle outlet; After entering the subsequent cycles (100–180 μs , 180–260 μs , 260–340 μs), the droplet strictly follows the three-stage evolution pattern of “growth necking detachment”: the liquid column continues to extend along the axis and draws liquid from the nozzle, the neck area gradually shrinks and refines, and finally dynamically fractures under the competition of surface tension and viscous force. It is worth noting that as the cycle progresses, the geometric shape of detached droplets gradually evolves from an initial irregular spherical shape to a well-defined and uniformly shaped regular spherical shape, reflecting the dynamic convergence trend of the system from initial transient fluctuations to stable output.

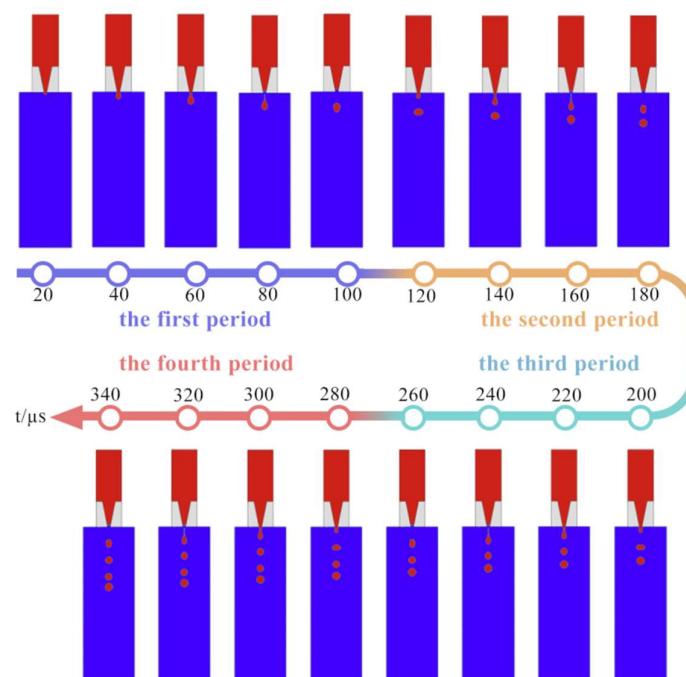


Figure 7. Characteristics of droplet growth desorption cycle.

This periodic droplet generation behavior not only explains the multi-physics coupling mechanism of “piezoelectric vibration flow field response droplet formation” from a mechanistic perspective, but also provides solid visual data support for the subsequent con-

struction of key output parameters such as droplet diameter, mass, desorption frequency and quantitative correlation models with input conditions such as driving voltage and fluid dynamic viscosity.

3.4. Analysis of the Mechanism of Action of Droplet Spray Performance Parameters

3.4.1. Driving Voltage

In order to clarify the influence mechanism of the pulse voltage amplitude on the droplet ejection behavior, this study operates under the premise of keeping the hydrodynamic viscosity and surface tension parameters constant by adjusting the pulse voltage amplitude applied to the piezoelectric ceramic, that is, selecting five gradients of 24 V, 48 V, 55 V, 110 V and 220 V; the evolution curve of the sound pressure of the center particle of the vibrator with time under different voltage conditions is thereby obtained (Figure 6). This set of sound pressure data will be used as the pressure inlet boundary conditions for the numerical simulation of gas–liquid two-phase flow, and the regulation mechanism of voltage parameters on the whole process of droplet generation will be revealed in depth.

Based on the analysis of the droplet motion morphology in Figure 8, it can be seen that under high-voltage conditions, the droplet head is spherical, and a large number of satellite droplets are derived from the tail. The neck ligament connecting the main droplet and the satellite droplet is thin and prone to necking and fracture, exhibiting typical “brushed dispersed fracture” characteristics; under low-voltage conditions, the droplet morphology is concentrated, the head is approximately small circular and there is no obvious satellite droplet or wire drawing fracture phenomenon. The overall structure is stable and compact. As the voltage amplitude changes from high to low, the droplet morphology gradually shifts from a dispersed state of “multiple satellite droplets + wire drawing fracture” to a concentrated state of “single droplets”, and the cervical ligament also gradually changes from slender and easily breakable to short, thick or even disappearing.

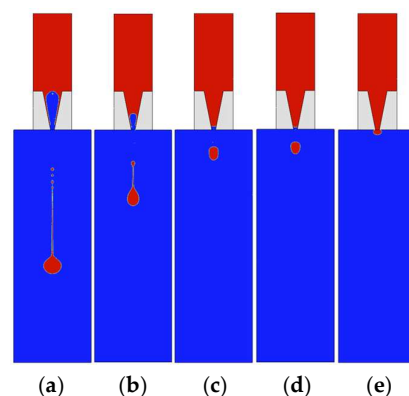


Figure 8. Diagram of droplet motion under different voltage amplitudes ($t = 100 \mu\text{s}$, dynamic viscosity = $0.005 \text{ Pa}\cdot\text{s}$). (a) 220 v; (b) 110 v; (c) 55 v; (d) 48 v; (e) 24 v.

In terms of droplet size, high voltage can cause significant secondary atomization, forming a group of extremely small and dispersed droplets; under low voltage, droplets do not undergo atomization fracture and exist as a whole, with relatively large and concentrated sizes. As the voltage gradually decreases, the average size of droplets shows an increasing trend, and the number of small-sized satellite droplets decreases significantly, while the proportion of large-sized main droplets increases significantly.

Based on the analysis of the variation law of oil spray velocity in Figure 9, an increase in driving voltage will significantly increase the spray velocity. When the driving voltage is 24 V, the spraying speed is only 0.5 m/s; when the voltage reaches 220 V, the speed increases to 17.8 m/s. This is because a higher driving voltage generates stronger driving

force for the piezoelectric device, enhancing the fluidity of the oil and thereby driving a significant increase in the ejection speed.

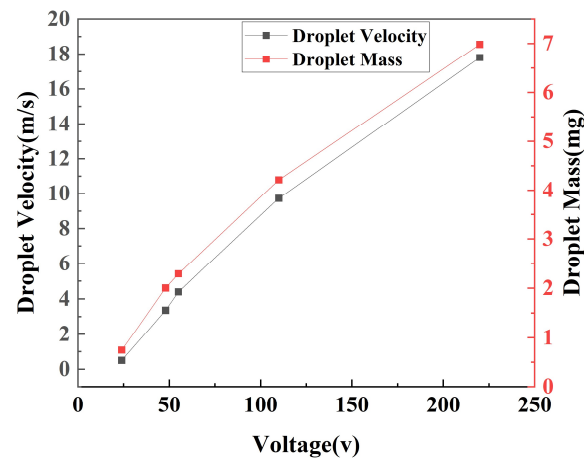


Figure 9. Droplet velocity and droplet mass under different voltage amplitudes.

In terms of the quality of oil spray, it continues to increase with the increase of driving voltage. When the driving voltage is 24 V, the sprayed mass is 0.74 mg; when the voltage is 220 V, the mass increases to 6.98 mg. Under high driving voltage, the piezoelectric device pushes more oil per unit of time and the degree of droplet aggregation before atomization is higher, resulting in a significant increase in the single sprayed mass.

In summary, under high driving voltage, the speed and quality of oil spray are higher, which is conducive to rapid and large-scale transportation of liquid droplets, and is suitable for parts of spacecraft that require efficient and high-flow lubrication; under low driving voltage, the oil spray speed is low, the mass is small, the process is smooth, and the droplet concentration is high, which is suitable for specific areas of precise low-dose lubrication. Flexible adjustment of driving voltage can meet the diverse micro-lubrication needs of spacecraft.

3.4.2. Dynamic Viscosity

To clarify the influence mechanism of fluid dynamic viscosity on droplet ejection behavior, this study compared five different dynamic viscosities while maintaining constant pulse voltage amplitude and surface tension parameters, revealing in depth the regulatory mechanism of this parameter on the entire droplet generation process.

Based on the analysis of the droplet motion morphology in Figure 10, it can be seen that as the dynamic viscosity increases, the head of the droplet tends to change from a “spherical” shape to a “droplet shaped” shape. When the dynamic viscosity is at a low level, the droplet head presents a regular spherical shape, and a highly developed satellite droplet is derived from the tail. The neck ligament connecting the main droplet and the satellite droplet is relatively thin, which is prone to necking and fracture, exhibiting typical “wire like fracture” characteristics. When the dynamic viscosity is high, the droplet head gradually transforms from a spherical shape to a droplet shape, making it difficult to experience wire drawing fracture under the action of airflow. Its morphological changes are more reflected in overall deformation or tearing, and the structure is relatively more concentrated.

In terms of droplet size, under low dynamic viscosity conditions, due to the sufficient development of the tail satellite droplet and the easy breakage of the neck ligament, the droplet will undergo significant secondary atomization, resulting in a smaller overall droplet population and more dispersed distribution. Under high dynamic viscosity conditions, droplets often exist in the form of overall deformation or tearing, resulting in larger droplet sizes and more concentrated distributions.

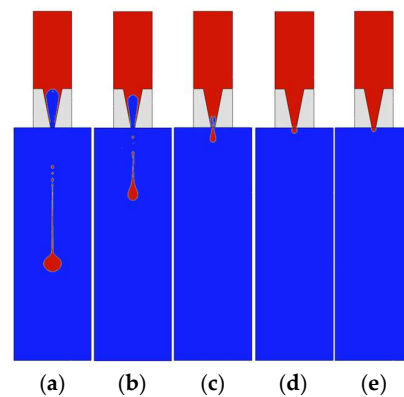


Figure 10. Diagram of droplet motion under different dynamic viscosities ($t = 100 \mu\text{s}$, $v = 220 \text{ v}$). (a) $0.005 \text{ Pa}\cdot\text{s}$; (b) $0.018 \text{ Pa}\cdot\text{s}$; (c) $0.045 \text{ Pa}\cdot\text{s}$; (d) $0.09 \text{ Pa}\cdot\text{s}$; (e) $0.16 \text{ Pa}\cdot\text{s}$.

Based on the analysis of the variation law of oil ejection velocity in Figure 11, it is found that as the dynamic viscosity increases, the ejection velocity of the oil decreases significantly. When the dynamic viscosity is $0.005 \text{ Pa}\cdot\text{s}$, the spraying speed can reach 17.8 m/s . At this time, the viscous resistance of the oil is small, and it can be quickly sprayed under piezoelectric drive; when the dynamic viscosity increases to $0.16 \text{ Pa}\cdot\text{s}$, the ejection velocity is only 1.14 m/s . This is because the high viscosity increases the viscous resistance inside the oil, greatly hindering its flow and leading to a decrease in ejection velocity.

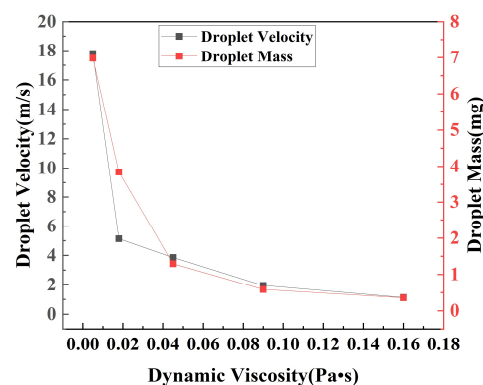


Figure 11. Droplet velocity and droplet mass under different dynamic viscosities.

In terms of the quality of oil spray, it shows a continuous decreasing trend with the increase of dynamic viscosity. When the dynamic viscosity is $0.005 \text{ Pa}\cdot\text{s}$, the sprayed mass is 6.98 mg , and the low viscosity oil has good fluidity. The piezoelectric device can push more oil per unit time, and the droplets are easy to concentrate and spray before atomization; when the dynamic viscosity rises to $0.16 \text{ Pa}\cdot\text{s}$, the ejected mass is only 0.35 mg , and the high viscosity oil has poor fluidity. The piezoelectric device is difficult to push a large amount of oil in a short period of time, and the droplets are not easily aggregated before being ejected, resulting in a significant reduction in the mass of a single ejection.

In summary, during the operation of the piezoelectric micro fuel supply system, low dynamic viscosity oil exhibits the advantages of high spray speed and large spray mass, which can drive the rapid formation of droplets to achieve a large-scale atomization effect. The small droplets generated after atomization have good compatibility with the core strategy of “small amount multiple times” required for spacecraft micro-lubrication, especially suitable for key parts that require high lubrication efficiency.

4. Conclusions

By analyzing the characteristics of droplet ejection, the following conclusions can be drawn:

- (1) Driving voltage—as an external factor that promotes the droplet ejection characteristics. As the driving voltage gradually increases, the driving force generated by piezoelectric excitation continues to increase, promoting the regular evolution of droplet morphology from a stable and concentrated single droplet overall state under low voltage conditions, gradually transitioning to a dispersed state with multiple satellite droplets coexisting and a neck prone to necking and fracture. During this process, the average particle size of the droplets significantly decreases, the spatial distribution tends to become more discrete and the droplet ejection velocity increases synchronously with the single ejection mass.
- (2) Dynamic viscosity—as an internal factor that inhibits the droplet ejection characteristics. With the continuous increase of dynamic viscosity, the internal viscous resistance of the oil significantly increases, resulting in a reverse evolution of droplet morphology from a wire-drawn fracture morphology of “spherical head + satellite droplet development” under low viscosity conditions, it gradually transitions to a water-droplet-shaped structure with overall concentration and stable mechanical state. At the same time, the average particle size of the droplets showed a significant increase, and the spatial distribution became more concentrated. The droplet ejection velocity and single ejection mass both showed a significant downward trend, and the droplet motion state exhibited a smoother flow characteristic.

The aforementioned conclusions reveal the regulation laws of driving voltage and dynamic viscosity on droplet ejection characteristics, enriching the understanding of liquid breakup mechanisms under microscale piezoelectric actuation. This can provide theoretical references for the optimal design of piezoelectric microdroplet ejection devices. It should be noted that this study is conducted based on room-temperature conditions and the continuum medium hypothesis, and the conclusions are valid within this scope. In the future, experimental verification will be incorporated, and factors such as evaporation and phase change in extreme space environments will be further considered to expand the applicability of the model.

Author Contributions: Conceptualization, Z.D. and J.D.; methodology, Z.D. and J.D.; validation, Z.D.; writing—original draft preparation, Z.D. and J.D.; writing—review and editing, all authors; supervision, Z.D. All authors have read and agreed to the published version of the manuscript.

Funding: National Key Research and Development Program of China (2023YFB3712300).

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the corresponding author upon request.

Acknowledgments: The research was supported by all authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Fan, X.Q.; Wang, L.P. Graphene with Outstanding Anti-irradiation Capacity as Multialkylated Cyclopentanes Additive toward Space Application. *Sci. Rep.* **2015**, *5*, 12734. [[CrossRef](#)] [[PubMed](#)]
2. Roberts, E.W. Space Tribology: Its Role in Spacecraft Mechanisms. *J. Phys. D-Appl. Phys.* **2012**, *45*, 503001. [[CrossRef](#)]
3. Yuan, J. Lubrication of Long-Life Medium-High Speed Rolling Bearings for Space Payloads. *Lubr. Eng.* **2006**, *6*, 154–158.
4. Yu, X.; Ai, J.; Yang, L.; Wang, C.B. Exploring Tribological Behaviour of Diamond Film by Hot-Filament Chemical Vapour Deposition on Tungsten Carbide for Lunar Exploration. *Vacuum* **2014**, *100*, 41–45. [[CrossRef](#)]
5. Yan, Z.; Sui, X.D.; Yan, M.M.; Liu, J.; Zhang, S.T.; Hao, J.Y.; Li, W.S.; Liu, W.M. Dependence of Friction and Wear on the Microstructures of WS₂ Films under a Simulated Space Environment. *ACS Appl. Mater. Interfaces* **2020**, *12*, 56632–56641. [[CrossRef](#)] [[PubMed](#)]

6. Wang, Z.A.; Chen, G.X. Research Progress on Lubrication Performance of Liquid Lubricants for Spacecraft. *Lubr. Eng.* **2008**, *33*, 138–141.
7. Sathyan, K.; Hsu, H.Y.; Lee, S.H.; Gopinath, K. Long-term lubrication of momentum wheels used in spacecrafts—An overview. *Tribol. Int.* **2010**, *43*, 259–267. [[CrossRef](#)]
8. Hashimoto, F. Ooze Flow Bearing. U.S. Patent 62903979(P), 18 September 2001.
9. Loewenthal, S.H.; Scibbe, H.W.; Parker, R.D.; Zaretsky, E.V. *Operating Characteristics of a 0.87 kWh Fly Wheel Energy Storage Module*; NASA Technical Memorandum; National Aeronautics and Space Administration: Washington, DC, USA, 1985.
10. Wang, Z.J. Study on Porous Oil-Impregnated Polyimide Cages for Gyro Bearings. Master's Thesis, Hefei University of Technology, Hefei, China, 2004.
11. Wang, Y.; Liu, Q.S.; Yan, J.P. Characteristic study on the porous reservoir of liquid lubricant in space. *Chin. J. Space Sci.* **2008**, *28*, 592–596. [[CrossRef](#)]
12. Sun, X.B.; Shang, X.H.; Li, K.Y.; Li, Y.Y.; Mai, N.N. Study on compatibility between porous polyimide cage and space lubricating oil. *Eng. Plast. Appl.* **2021**, *49*, 109–114.
13. Sathyan, K. *Long-Term Lubrication Systems for Momentum Wheels Used in Spacecrafts*; Indian Institute of Technology Madras: Chennai, India, 2003.
14. Dou, Z.L.; Song, A.J.; Li, J.X.; Zhou, G.; Zhang, S.H.; Si, L.N.; Liu, F.B. Development and performance testing of a small amount of oil supply device for space. *Lubr. Eng.* **2023**, *48*, 80–85.
15. Shan, T.Y.; Sun, D.F.; Cao, Z.Y. Research on Jet Characteristics of Piezoelectric Micro-Jet Active Oil Supply Device. In Proceedings of the Symposium on the Development Trend and Direction of Inertial Technology—New Inertial Components and Advanced Navigation Technology, Shanghai, China, 9 August 2023.
16. Tian, X.Q.; Liu, Y.X.; Deng, J.; Wang, L.; Chen, W.S. A review on piezoelectric ultrasonic motors for the past decade: Classification, operating principle, performance, and future work perspectives. *Sens. Actuators A Phys.* **2020**, *306*, 111971. [[CrossRef](#)]
17. Wang, L.; Chen, W.S.; Liu, J.K.; Deng, J.; Liu, Y.X. A review of recent studies on non-resonant piezoelectric actuators. *Mech. Syst. Signal Process.* **2019**, *133*, 106254. [[CrossRef](#)]
18. Huang, B.; Wei, Y.; Lu, K.J.; Wang, L.B. Study on Output Efficiency of Piezoelectric Stacks Transducer in Road Vibration Environment. *J. Highw. Transp. Res. Dev.* **2016**, *33*, 37–43.
19. Yang, X.; Zhou, Z.Y.; Ye, X.Y.; Li, N.; Zhao, H.Z.; Luo, X.B. A Diaphragm Micro Air Pump Actuated by Piezoelectric Element. *Piezoelectrics Acoustooptics* **2005**, *4*, 365–368.
20. Li, W.X. Research on Active Oil Supply Technology for Shafting Based on Piezoelectric Jet of Microfluid. Master's Thesis, Harbin Institute of Technology, Harbin, China, 2019.
21. Lefebure, A.; Shim, D. Ultrasonic Atomization of Highly Viscous Biodegradable Oils for MQL Applications. *J. Mech. Sci. Technol.* **2021**, *35*, 5503–5516. [[CrossRef](#)]
22. Sun, J.H. Research on Micro Active Lubrication Device for Space Bearings Based on Piezoelectric Drive. Master's Thesis, Harbin Institute of Technology, Harbin, China, 2022.
23. German, G.; Bertola, V. Formation of Viscoplastic Drops by Capillary Breakup. *Phys. Fluids* **2010**, *22*, 71–82. [[CrossRef](#)]
24. Liu, Y.J. Experimental and Numerical Study on the Droplet Formation Characteristics of Newtonian Fluid. Master's Thesis, Zhejiang Sci-Tech University, Hangzhou, China, 2018.
25. Yang, Y.J.; Zhang, W.; Zheng, S.L.; Xu, L.H.; Chen, B.B. Experimental and Simulation Studies on Dynamic Formation of Sodium Alginate Drops in Miniature Tubes. *J. Chem. Eng. Chin. Univ.* **2016**, *30*, 1264–1273.
26. Ye, L. Research on Piezoelectric Micro-Jet Device Based on Resonant Drive. Master's Thesis, Harbin Institute of Technology, Harbin, China, 2015.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.