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Simulation and Analysis of Influence of Vacuum Back Pressure Environment on Laser Thruster

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Abstract: The paper presents a simulation physical model of laser thruster under vacuum back pressure environment. Through the finite difference method and the Direct Simulation Monte Carlo (DSMC) calculation method, based on the actual laser thruster structure and working mode, the changes of the flow field distribution in the laser thruster plume under different vacuum back pressure conditions are obtained. The influence of different vacuum back pressure conditions on the plume density field and velocity field of the thruster was verified through physical experiments, and the evolution process of the plume flow field during laser ablation of polyamide glycidyl ether (GAP) solid target material was analyzed in detail. The simulation results are in good agreement with the test results, and the deviation between the simulated data and the test data from 0 to 3000ns is less than 10.4%. It presents a foundation for the prediction model of laser thruster under vacuum environment, and provides an important reference for ground test and in-orbit application of satellite laser propulsion system.

Keywords: laser thruster; vacuum backpressure; plume; simulation

1. Introduction

Laser propulsion is a new technology that holds promise for use in future aerospace propulsion applications [1,2]. Compared with traditional chemical [3] and cold gas [4] propulsion technology, it has the advantages of high specific impulse and high propulsion efficiency. And due to the lightweight of the propulsion system, the payload can be increased, with a payload ratio of over 15%, greatly reducing launch costs [2,5,6]. Since 2000, China has made significant progress in the research of laser propulsion technology, and the demand for research projects related to the characteristics of laser thruster has gradually increased [7-9]. However, there are many problems need to be solved in the relevant technologies.

The flow field of thruster under vacuum back pressure environment directly influences the working effect, service life and pressure transfer effect of thruster[10]. The flow field under vacuum back pressure environment not only concerns the relevant characteristics of thruster, but also impacts the aircraft load near the convection and solar array once the plume field formed after the on-orbit thruster is ignited, causing the effects of mechanics, thermal load, charge accumulation and surface contamination[10-13]. These effects will lead to the uncontrolled movement of the aircraft in orbit, and damage to the optical sensitive elements carried by the solar array and the aircraft, and have a serious impact on the sensitive elements such as the optical devices, thermal control coatings and the surface of the solar wing of the spacecraft, leading to performance degradation and even complete failure of a system or component. Therefore, more and more attention has been paid to the research of the flow field of the spacecraft thruster under the vacuum back pressure environment.

At present, the simulation of flow field of thruster under high vacuum environment generally adopts two calculation methods: continuous flow and molecular flow. For the pressure field, velocity field and density field of thruster of spacecraft at high altitude, N-S equation and Monte Carlo method are the basic simulation analysis methods [14,15]. Research on high-altitude flow field calculation and experimentation was conducted earlier abroad, however few research data is available in this area because the gas density in the backflow area is much smaller than that in the

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forward flow area, which brings some difficulties to the simulation and test [16,17]. Domestic research is just in its infancy [18,19]. This paper establishes a physical model of laser thruster ignition under the vacuum back pressure environment, and carries out simulation and analysis of flow field and experimental research to obtain important basic data, and lays a foundation for the influence law of flow field distribution in the working state of laser thruster, on-orbit verification and application.

2. Physical Model Analysis of Ignition Process of Laser Thruster under Vacuum Back Pressure Environment

2.1. Physical modeling

First, the geometric model of laser thruster is established based on the actual structure of laser thruster, and the structure is refined for the key positions for analysis of flow field to obtain the ignition geometric model of laser thruster. And then, a physical model of ignition under the space vacuum environment where the thruster is located is built based on the location, material properties, mechanical properties and thermal properties of thruster. Due to the fact that the engine is axisymmetric, in order to simplify the model to cut down the calculation, the model is axially divided, and the bottom of the model is set as the mirror plane. The schematic diagram of the model is shown in Figure 1.

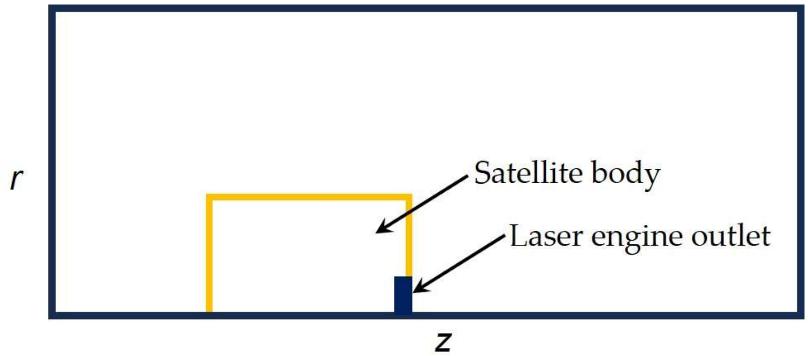

Figure 1. Establishment of simulation analysis model of laser thruster.

Due to the fact that the model of laser thruster mechanism is relatively regular, the square grid division method is used. For the inlet, the start of the convergent section of the nozzle is selected, and grid refinement is performed near the nozzle outlet and the axis. The grid division is shown in Figure 2.

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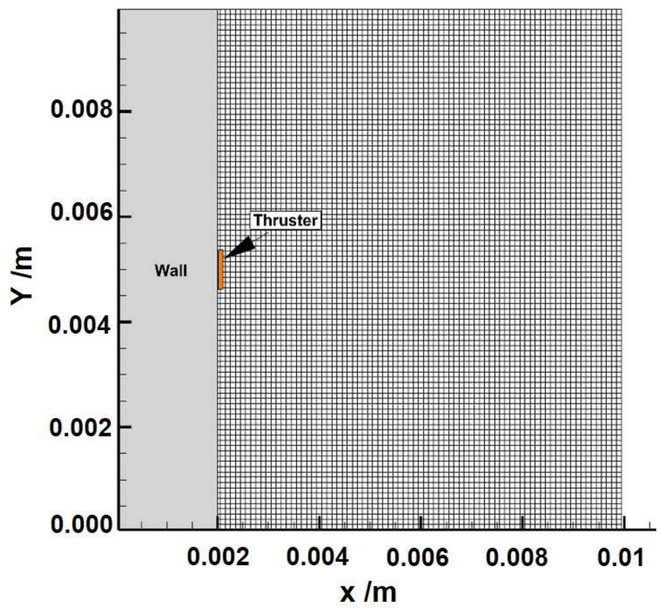

Figure 2. Grid division of model.

The vacuum back pressure value of the environment where the laser thruster is located is used as the initial boundary input condition for each vacuum back pressure operating condition, and the simulation results under different back pressures can be obtained by changing the ambient back pressure without changing other boundary conditions. The input boundary condition parameters of laser thruster under excited status, such as initial velocity vector of laser thruster, temperature and pressure or number of molecules, are analyzed. Some data need to be obtained by testing, while some data need to be obtained by calculation, and then the above parameters are used as the inlet boundary conditions for analysis.

The laser of transmissive laser thruster laser hits the target material through the transparent layer, and the target material absorbs the energy and generates the thrust in the process of sputtering. The whole model is built based on a one-dimensional theoretical model of shock propagation. In the process of laser micro ablation, the transparent layer is used as the bearing structure of thrust force and is not expected to be ablated or destroyed. In the actual design process, the material with good ablation resistance, light transmittance and certain impact resistance is usually used. Therefore, the transparent layer (constraint layer) is considered as a solid wall during modeling, and does not exchange energy with other parts. As shown in Figure 3, the laser passes through the transparent layer (constraint layer), irradiates on the target surface of the interlayer working medium, heats, melts, gasifies the working medium at a certain depth, and further ionizes to form a high-temperature and high-pressure plasma in a short time, and at the same time, forms a shock wave that propagates into the working medium. The plasma further absorbs the laser energy to the end of the laser and expands rapidly outwards, compressing the target material until the remaining target material is pushed out as a whole and out of the working medium target.

The ignition stage of laser thruster is generally divided into absorption stage, target material detachment stage and jet burst stage. The absorption stage is that when the laser irradiation occurs, the energy is $I(t)\,\mathrm{d}t$. The laser passes through the transparent layer with its energy attenuated due to the blocking and absorption of the transparent layer. The target material absorbs the laser energy of λ times $I(t)\,\mathrm{d}t$, where λ is the absorption efficiency coefficient. The target material detachment stage is that when the intensity of pressure of the compressed target material is less than that corresponding to the plastic deformation of the target material, the target material is released and detached from the transparent layer; The jet burst stage is characterized by a short detachment time of the target material. At the moment of detachment, the target material and the high-temperature and high-

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pressure gas inside begin to jet and burst. High-energy particles with laser energy diffuse freely in the cosmic environment, forming a plume field during the jet process.

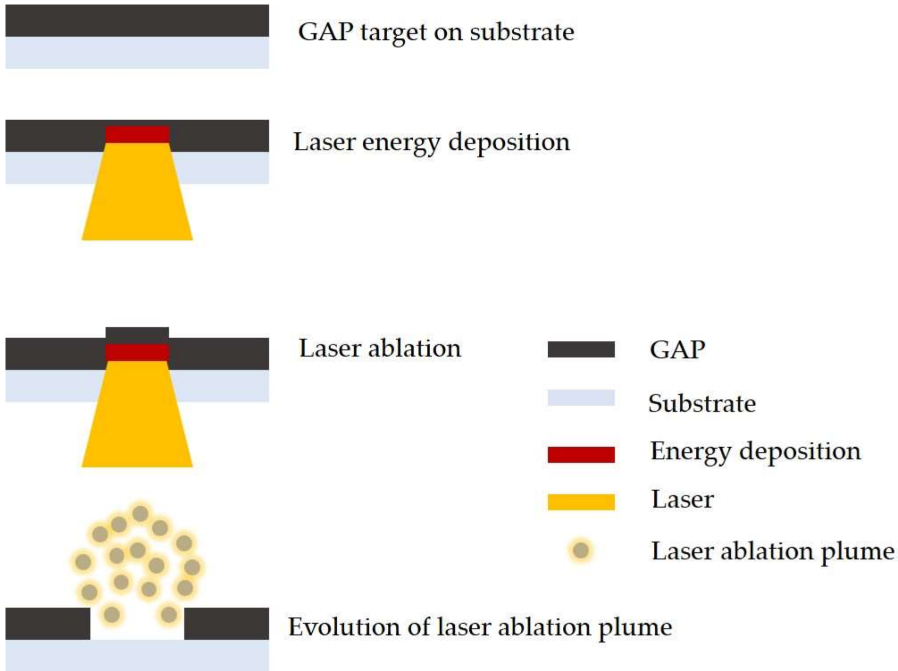

Figure 3. Physical model of ignition process.

2.2. Simulation Analysis Method

The flow field of laser thruster under different vacuum back pressure includes complex continuous medium flow, transitional domain flow and free molecular flow. In the research process of numerical simulation method, it is necessary to establish corresponding mathematical and physical models for different flow conditions and adopt numerical simulation methods that are suitable for them. This study adopts both macroscopic and microscopic methods for modeling flowing gas. Macroscopic modeling is the process of considering gas as a continuous medium and analyzing the gas flow field using N-S equation, while microscopic modeling is the process of considering gas to be composed of countless discrete molecules, describing the flow field using the Boltzmann equation, and numerically solving it using the Direct Simulation Monte Carlo (DSMC) method or approximating it using engineering model [12]. The Knudsen Number (Kn), defined as the ratio of the molecular mean free path to the object characteristic length, is usually used as the criterion for describing continuous flow: 1) Kn<0.1 for the continuum regime, modeled using the N-S equation; 2) 0.1<Kn<10 for the transitional flow regime, and the assumption of continuum is no longer valid. Molecular gas dynamics must be applied for research; 3) Kn>10 for the regime of free molecular flow, which can only consider the interaction between molecules and objects, ignoring the collision between gas molecules, thus greatly simplifying the problem solving. This research adopts segmentation for the flow field analysis of thruster under different back pressure environments: the finite difference method is used to solve the N-S equation in the engine nozzle; DSMC method is used in the flow field outside the nozzle; and in the free molecular flow region outside the nozzle, the motion of gas molecules and mutual expansion are microscopically numerically simulated to obtain the distribution of flow field outside the nozzle. The location diagram is shown in Figure 4.

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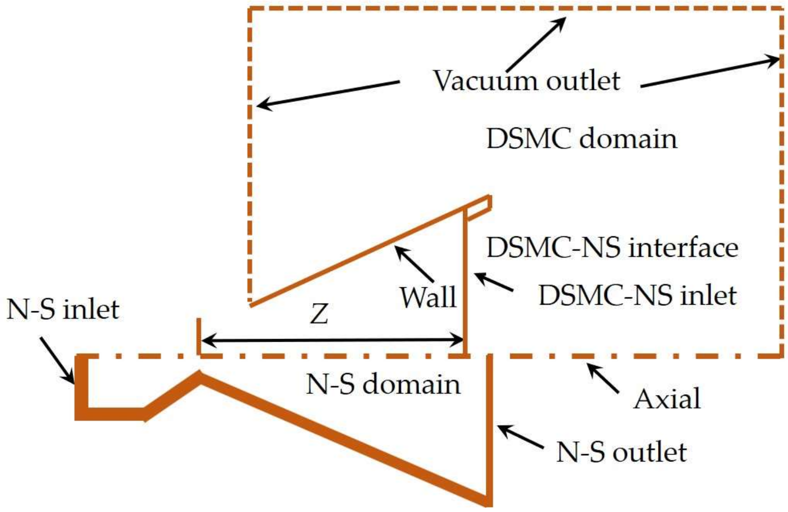

Figure 4. Region division by boundary condition.

The implementation process of DSMC method in molecular flow mainly consists of 7 steps, namely initialization (in this step, the number of molecules is set to distinguish different vacuum back pressure environments), setting the initial position and velocity of molecules entering the flow field, simulating molecular motion, simulating molecular renumbering, collision sampling, determining whether to sample, and statistical analysis of macroscopic quantities in the flow field.

In this research, the DSMC method is used to investigate model changes during this process. It could simulate the collision process between product gas molecules, between product gas and environmental gas, and between product gas and wall. An under-relaxation technique is used to achieve transient DSMC simulation. The transparent layer is set to a wall and rebound all particles that collide with it in the form of cosine theorem. The initial velocity V0 is used as the initial condition for the GAP material after absorbing energy and leaving the transparent layer. The burst process involves the free diffusion of high-speed particles (DSMC simulation), forming a plume field during the ignition process. The DSMC simulation analysis diagram is shown in Figure 5.

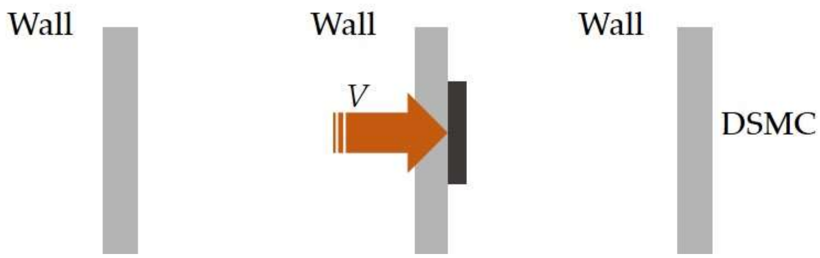

Figure 5. DSMC analysis model.

3. Simulation Test Results and Discussion

3.1. Test results

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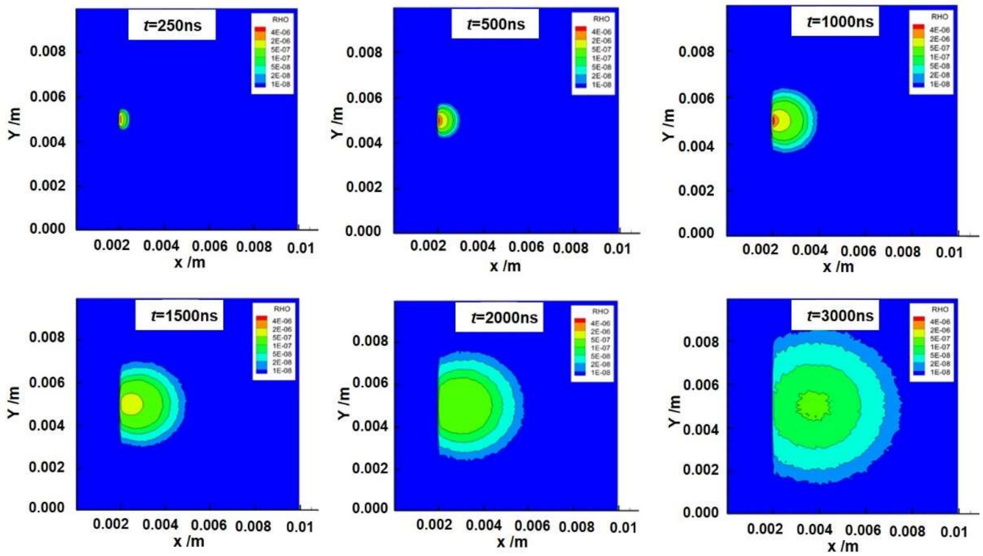

Figure 6. Density cloud during operation of laser thruster.

By simulation analysis and calculation, the density calculation results during the operation of the laser thruster are obtained. The simulation results in Figure 6 show that the density of the ejected particles at the moment they detach from the target material is the highest, reaching 4×10^{-6}Kg/m^3. As the ejected particles gradually expand towards the cosmic environment, they undergo diffusion, and the density of the ejected particles gradually decreases. Moreover, the position with the highest density in the ejected particle cloud map gradually moves forward over time. Compared with the particle diffusion profile, it is not difficult to find that the moving speed at the position with the highest density is lower than the propulsion speed of front of the ejected particles.

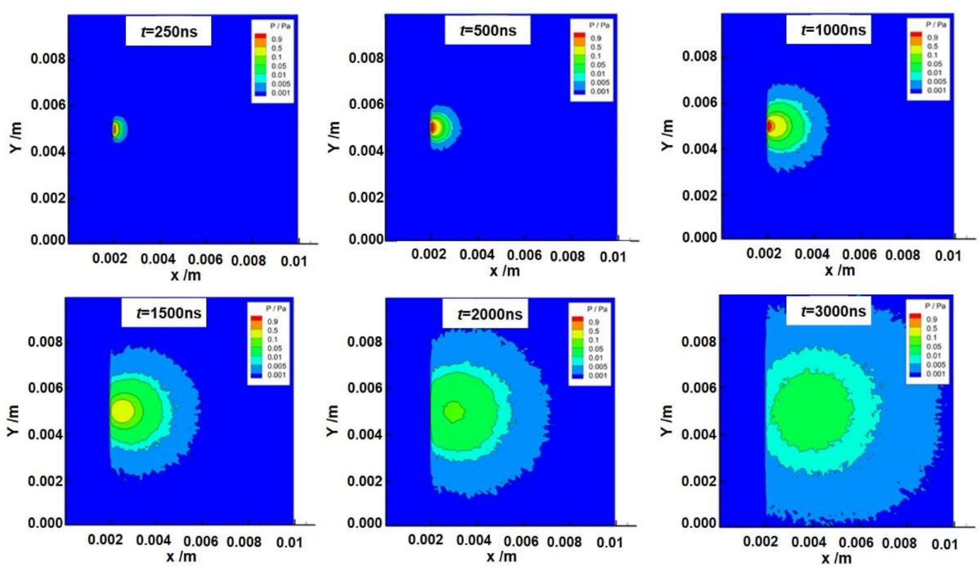

Figure 7. Pressure cloud during operation of laser thruster.

By simulation calculation, the pressure calculation results during the operation of the laser thruster are obtained. As shown in Figure 7, the pressure of the ejected particles at the moment they detach from the target material is the highest, reaching 0.9 Pa. As the ejected particles gradually expand towards the cosmic environment, they undergo diffusion, and the pressure of the ejected

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particles gradually decreases. Moreover, the position with the highest pressure in the ejected particle cloud map gradually moves forward over time.

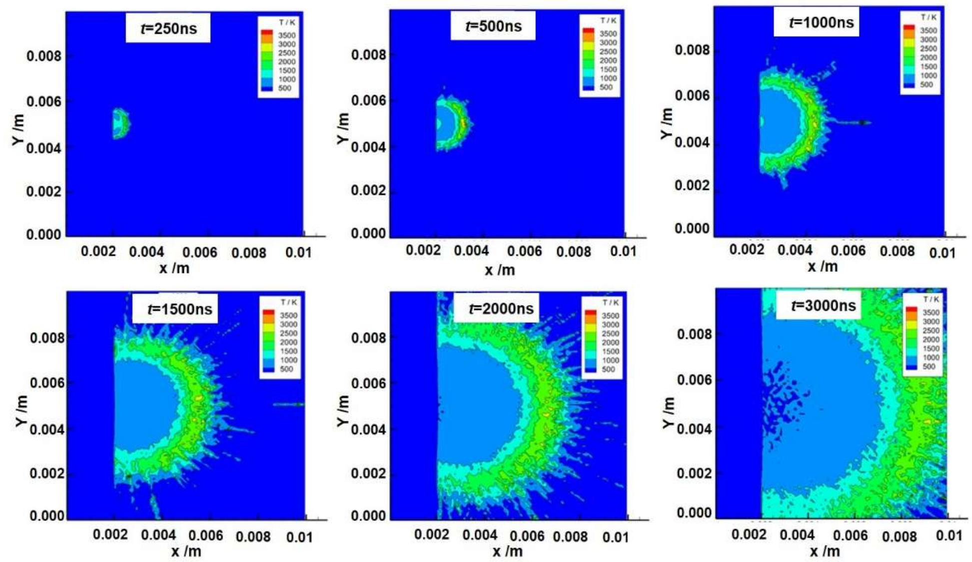

Figure 8. Temperature cloud during operation of laser thruster.

By simulation calculation, the temperature calculation results during the operation of the laser thruster are obtained. The simulation results in Figure 8 show that the higher the energy and velocity of the ejected particles, the higher the temperature. Therefore, the front of the temperature field cloud map is somewhat similar to the front of the velocity field. The temperature at the moment of ejecting is the highest, reaching 3000K.As the ejected particles expand towards the cosmic environment, the faster ejected particles move forward, and the high-speed particles always appear at the front of the ejection waveform. The ejected particles will collide with other ejected particles or particles in the universe during the expansion process, resulting in a loss of ability and a decrease in velocity. Therefore, the number of ejected particles with velocities greater than 2000 m/s will gradually decrease over time.

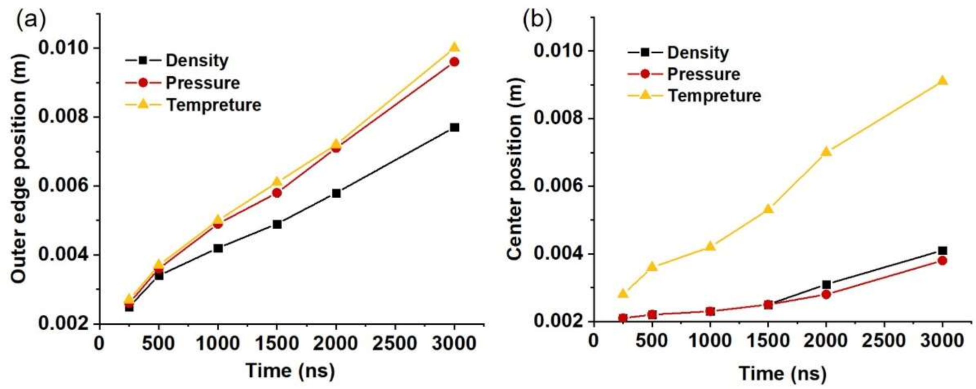

Figure 9. (**a**) The variation of outer edge position of plume density, pressure, and temperature with the feather flow field evolution time; (**b**) The variation of the center position of plume density, pressure, and temperature with the feather flow field evolution time.

In order to compare the changes in density, pressure, and temperature of laser ablation plumes with evolution time, the outer edge and center positions of the laser ablation plume were recorded in

Figure 9 (a, b). From the figure, it can be seen that the evolution speed of the plume flow field parameters from fast to slow is temperature, pressure, and density, respectively. The three parameters show a linear relationship with the evolution time of the flow field (250-3000ns). The center position of the plume temperature in Figure 9 (b) is significantly faster than the density and pressure, mainly due to the absorption mechanism of the millisecond laser ablation target material and the incompletely ionized plume products [7,20]. In addition, it can be seen from the simulation results that after laser ablation of the target material, the center point positions of various physical parameters gradually diffuse outward over time, rather than spreading outward in a standard hemispherical shape.

3.2. Test verification and analysis

In order to verify the correctness of the simulation test results of the laser thruster, the simulation results at each time segment are compared with the measurement results of the ignition test image of the plume field captured by the high-speed camera.

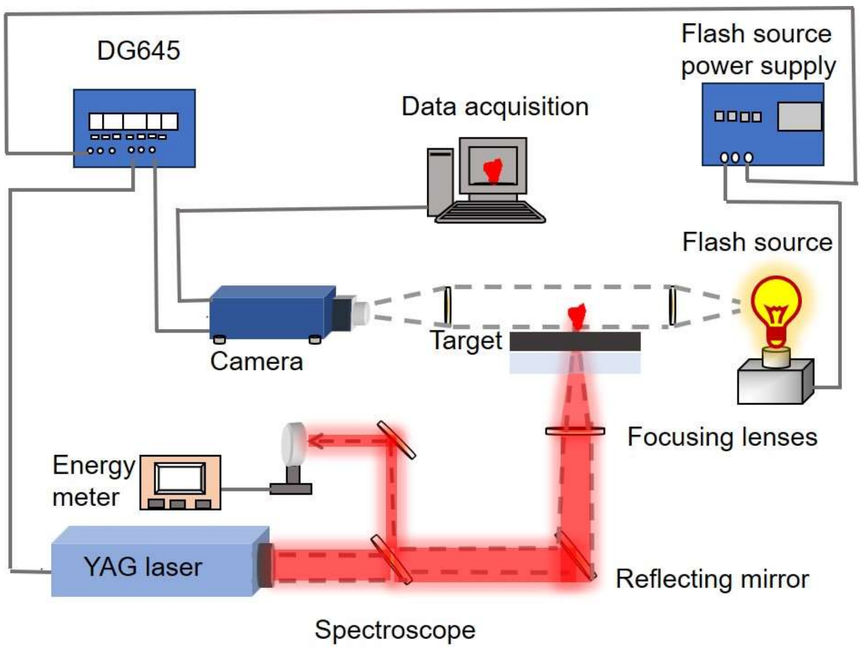

Figure 10. The feather flow field evolution testing system.

The feather flow field testing system is shown in Figure 10, and the entire schlieren system is tested under vacuum conditions in a vacuum chamber. The energy of the semiconductor laser in the figure is 40mJ, the pulse width is 100us, and the laser ablation mode is pulsed. The target material is GAP on a transparent PET substrate. Flash sources are used to supplement light intensity. High speed cameras are used to capture images of flow field evolution, with a minimum exposure time of 3ns. The signal transmitter (DG645) is connected to the laser, high-speed camera, and flash source to adjust the working timing of the three. After the laser emits light, DG645 sends signals to high-speed cameras and flash sources to capture and photograph the evolution of the plume. The evolution process of the plume flow field for a single pulse is analyzed. The illustrations in Figures 11 (a-d) show schlieren images under different exposure time conditions. From the results, it can be seen that significant shock waves are generated at 500ns, 1500ns, and 3000ns, and the coincidence with the outer edge of the shock wave in the simulation results is relatively high. From the experimental results, it can be seen that GAP target material is not completely ionized under the action of laser. The laser ablated plume material is ejected from the target surface, and the shape of the plume ejected is semi-circular. The shock wave formed by the laser is rapidly ejected outward along the direction of the jet.

From the shaded part of the high-speed camera image, it can be seen that the edge of shadow of the plume development should be the front of the plume shock wave. Therefore, the edge of shadow in the image is compared with the density simulation results. The comparison between the test images and simulation results of the laser-transmitted plume region is shown in Figures11 (a-d). The comparison time points selected for this research are set at 500 ns, 1500 ns, 2000 ns, and 3000 ns.

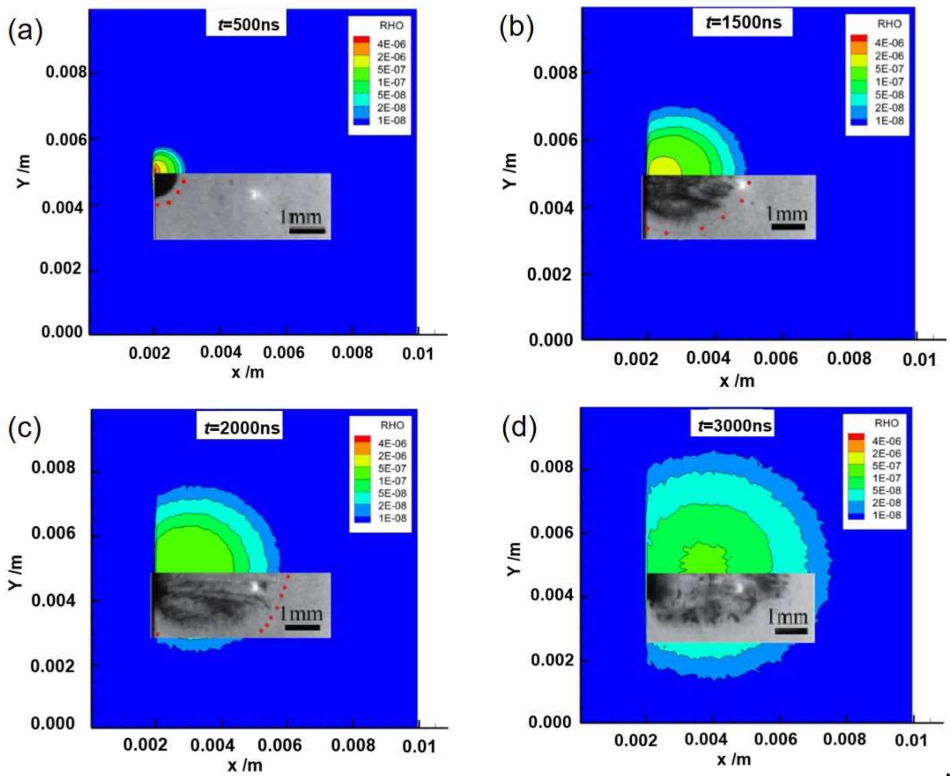

Figure 11. (**a**) Comparison between simulation and captured Images at 500 ns; (**b**) Comparison between simulation and captured Images at 1500 ns; (**c**) Comparison between simulation and captured Images at 2000 ns; (**d**) Comparison between simulation and captured images at 3000 ns.

The simulation results show a certain correlation between the shock front and density front at 500 ns, 1500 ns, and 2000 ns, and the consistency is high. The shock front disappears in the image captured by the high-speed camera at 3000 ns. Although the shock front cannot be compared, the central position of density in the image at 3000 ns is consistent with the simulation results. From the above simulation and experimental results, it can be concluded that a foundation for the prediction model of laser thruster under vacuum environment was successfully established, and provides an important reference for ground test and in-orbit application of micro/nanosatellite laser propulsion system.

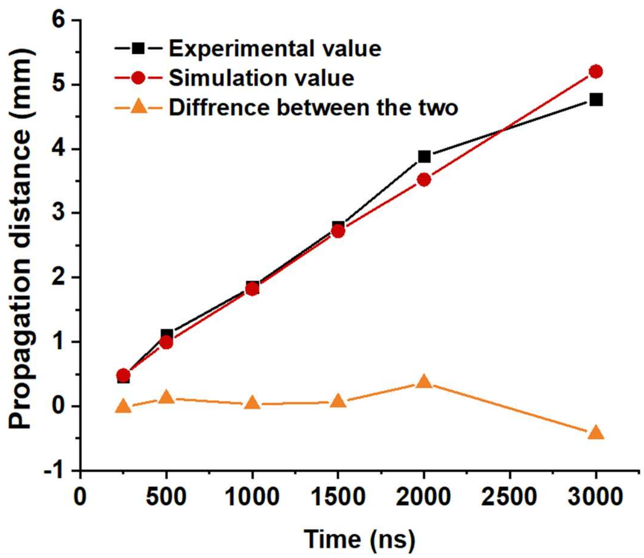

Figure 12. Comparison between experimental value and simulation value at the density front.

Figure 12 shows the comparison between the simulation value at the density front and the experimental value at the shock front, showing that the simulation value and experimental value are in good consistency, with a difference of less than 10.4% between the two from 0 to 3000 ns. And thus, it can be seen that the actual plume field generated by laser micro ablation of target material is consistent with the results obtained from theoretical model simulation, which verifies the correctness of the simulation result of this model, and provides an effective means for predicting the flow field for laser thruster ignition test under vacuum environment.

4. Conclusions

Laser propulsion is a new technology, highly valued for its advantages such as high specific impulse, high efficiency of propulsion, and high payload ratio compared to traditional chemical propulsion technology, and it has important application prospects in the future aerospace field. In this paper, the simulation physical model of ignition of laser thruster under vacuum back pressure environment is proposed that based on the actual structure and working mode of laser thruster, the changes in flow field distribution in the plume range of laser thruster under different vacuum back pressure environments is obtained by finite difference method and the DSMC method, and the influence of different vacuum back pressure environments on the plume velocity field and pressure field of laser thruster are verified by physical experiments. The simulation results are in good consistency with the experimental results, with a difference of less than 10.4% between the two from 0 to 3000 ns. This lays the foundation for the prediction model of laser thruster ignition test under vacuum environment, and provides important reference for ground experiment and on-orbit application of satellite laser propulsion system.

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References

1. Abbas, A.; Iqbal, S.T.; Jamil, Y. Ablative laser propulsion, the propellants and measuring parameters: A brief review. *J. Laser Appl.* **2024**, 36, 021201.
2. Yu, H.C.; Li, H.Y.; Wang, Y.; Cui, L.G.; Liu, S.Q.; Yang, J.; Brief review on pulse laser propulsion. *Opt. Laser. Technol.* **2018**,100, 57–74.
3. Chen, J.; Li, G.X.; Zhang, T.; Wang, M.; Yu, Y.S.; Experimental investigation of the catalytic decomposition and combustion characteristics of a non-toxic ammonium dinitramide (ADN)-based monopropellant thruster. *Acta Astronaut.* **2016**, 129, 367–373.
4. Martínez Martíneza, J.; Lafleurb, T. On the selection of propellants for cold/warm gas propulsion systems. *Acta Astronaut*. **2023**, 212, 54–69.
5. Jiao, L.; Cai, J.; Ma, H.H.; Li, G.X., Li, L.; Shen, Z.W.; Tang, Z.P. Research on applications of rectangular beam in micro laser propulsion. *Appl. Surf. Sci.* **2014**, 301, 481–487.
6. Wang, S.B.; Du, B.D.; Du, B.S.; Zheng, Y.Z.; Hong, Y.J.; Ye, J.F; Xing, B.Y.; Li, C.L.; Zhang, Y.H. Impacts of laser pulse width and target thickness on laser micro-propulsion performance. *Plasma Sci. Technol.* **2022**, 24, 105504.
7. Du, B.S.; Zheng, Y.Z.; Mao, C.T.; Cui, H.C.; Han, J.H.; Jiang, L.Y.; Ye, J.F.; Hong, Y.J. Transmissive Mode Laser Micro-Ablation Performance of Ammonium Dinitramide-Based Liquid Propellant for Laser Micro-Thruster. Micromachines **2023**, 14, 1219.
8. Lemmer, K. Propulsion for CubeSats, *Acta Astronaut.* **2017**, 134, 231–243.
9. Xu, R.P.; Tang Z.P. Numerical simulation for laser propulsion of air breathing mode considering multi-pulses. *High Power Laser and Particle Beams* **2007**, 19 (3): 369–372.
10. Bondar, Y.A.; Schweigert, V.A.; Ivanov, M. S. Modeling of the hall-effect thruster plume by combined PIC-MCC/DSMC method. *AIP Conf. Proc.* **2003**, 663: 549-556.
11. Nishii, K.; Levin, D. A. Three dimensional kinetic simulations of carbon back sputtering in vacuum chambers from ion thruster plumes. *J Propul. Power*. **2024**, 40(1), 123–137.
12. Fang, H.K.; Oyama, K.I. Cheng, C.Z. Plasma measurements in the space plasma operation chamber (SPOC). *Chinese J. Phys.* **2015**, 53(1), 123–137.
13. Aslanov, V.S.; Ledkov, A.S. The ion beam interceptor concept for a space station collision avoidance with space debris. *Acta Astronaut.* **2024**, 223, 49–57.
14. Tan, R.;Hang, G.R.; Wang, P.Y. Optimization of magnetic field design for Hall thrusters based on a genetic algorithm. *Plasma Sci. Technol.* **2024**, 26, 075503.
15. Yamashita, Y.; Tsukizaki, R.; Nishiyama, K. Effect of ion beam extraction on neutral density distribution inside a gridded microwave discharge ion thruster. *Vacuum* **2022**, 200, 100962.
16. Richard J. T.; Trevor M. M. Computational investigations of performance improvements for microlaser ablation plasma thrusters using nozzles. *IEEE T.Plasma. Sci.* **2011**, 39(11), 2932–2933.
17. Boyd, I.D.; Keidar, M. Simulation of the plume generated by a micro laser-ablation plasma thruster. In Proceedings of the High-Power Laser Ablation IV, PTS 1 AND 2 4760 2002; pp. 852–866
18. Tang, Z.P.; Xu, R.P. Numerical study on thermal mechanical impact failure mechanism for annular focusing laser thrusters. *AIP Conf. Proc.* **2010**, 111, 1230.

 doi:10.20944/preprints202501.2267.v1

19. Chen, H.; Shi, L.; Ma, L.H.; Chen, Y.G. Numerical simulation of air-breathing nanosecond laser propulsion considering subsonic inflow and multi-pulse. *Optik.* **2014**, 125(14), 3444-3448.
20. Mao, C.T.; Jing, L.Y.; Du, B.S.; Zheng, Y.Z.; Cui, H.C.; Wang, D.K.; Ye, J.F.; Han, J.H.; Hong, Y.J. Theoretical investigation of laser ablation propulsion using micro-scale fluid in atmosphere. *Aerospace.* **2024**, 11(8), 622-3448.