

Expansion Characteristics of a Plasma Jet in the Stepped-Wall Chamber Filled with Water

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Abstract

The interaction mechanism between the plasma and liquid is a key problem for the electrothermal chemical launch technology. To investigate this problem, a simulated experiment for the expansion process of a plasma jet in the working fluid is carried on. Based on this experiment, a two-dimensional axisymmetric unsteady theoretical model is established to reveal the plasma-liquid interaction flow field pattern. The results show that a typical Taylor cavity forms as the plasma jet expands in liquid. The induction effect of the stepped-wall structure enhances the radial expansion of the plasma jet. An arc-shaped pressure wave is generated at the front of the plasma jet and then evolves into the plane wave. A high-pressure area forms at the head of the plasma jet and then moves downstream. There is a strong plasma-liquid turbulent mixing at the interface, especially near the steps and the nozzle exit area.

Keywords

Electrothermal Chemical Launch, Plasma Jet, Stepped-Wall Chamber, Plasma-Liquid Interaction

1. Introduction

Electrothermal chemical launch technology, which is an advanced high-velocity propulsion technology, is widely interested by scholars [1]. The propulsive energy of electrothermal chemical gun consists of electrical energy input and the chemical energy from propellant combustion. Since the 1980s, more than a dozen countries such as the United States, Germany, and South Korea have started working on electrothermal chemical launch technology [2] [3] [4].

Electrothermal chemical guns can be classified into solid propellant electro-

thermal chemical guns [5] [6] and liquid propellant electrothermal chemical guns (LPETCG). Compared with solid propellant, liquid propellant has a higher packing density and chemical energy and is easy to realize loading automation. Therefore, liquid propellant has a good development prospect. However, there are complex phenomena including heat transfer, plasma expansion, liquid breakup, droplet entrainment, and vortex evolution during the interior ballistics process of LPETC guns. There even is the gun bore explosion accident in the internal ballistic process of the LPETCG. The crucial reason is the core scientific problem—the interaction mechanism of the plasma jet and liquid is not clear now. Therefore, it is necessary to investigate the expansion process and characteristics of the plasma jet in liquid and find a suitable method to control the stability of the liquid propellant combustion.

The concept of using a stepped-wall structure in the liquid chamber was introduced as a potential mean of controlling the combustion of bulk-loaded liquid propellant [7], and this approach was further developed and tested by experimental and numerical research [8] [9]. Further, the stepped-wall structure in the liquid chamber is also an efficient way to control the plasma-liquid interaction. Yu [10] revealed that the axial expansion speed of the plasma jet in the stepped-wall liquid chamber is greater than in the traditional cylinder chamber. Zhang [11] found that the radial turbulence of the plasma jet is enhanced in the stepped-wall liquid chamber. Further, increasing the stepped-wall liquid chamber's extension factor (ratio of the step diameter to the step height) can reduce the axial turbulence of plasma jet [12].

In this work, the evolution process of a plasma jet in the stepped-wall liquid chamber with four steps was observed by the experiment. Based on the experiment, a two-dimensional axisymmetric unsteady mathematical physics model of a plasma jet expanding in water was established to study the expansion characteristics of a plasma jet, as well as the pressure evolution in the plasma-liquid interaction flow field. The results can provide a reference to investigate the interaction mechanism of the plasma jet and the ambient liquid.

2. Experiment

2.1. Experimental Device

To study the interaction mechanism of the plasma jet and the working fluid, an experimental device was designed including a pulse power source, a plasma generator, and liquid chamber. The pulse power source mainly included a pulse-forming network, as shown in **Figure 1**. The role of the plasma generator was to generate the high-temperature and high-pressure plasma. The plasma generator was the load of the pulse-forming network, so the plasma generation process could be controlled by setting discharge voltages.

The plasma generator (shown in **Figure 2**) mainly consists of polyethylene capillary, exploding wires, electrodes, insulators, and metal shells. The polyethylene capillary was connected to the pulse power source by a pair of electrodes.

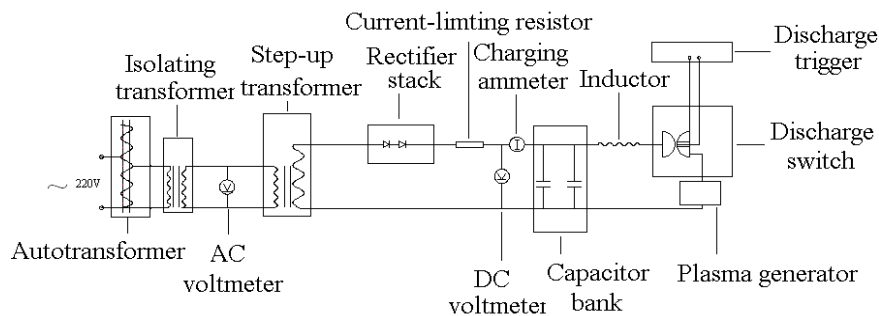


Figure 1. Pulse-forming network.

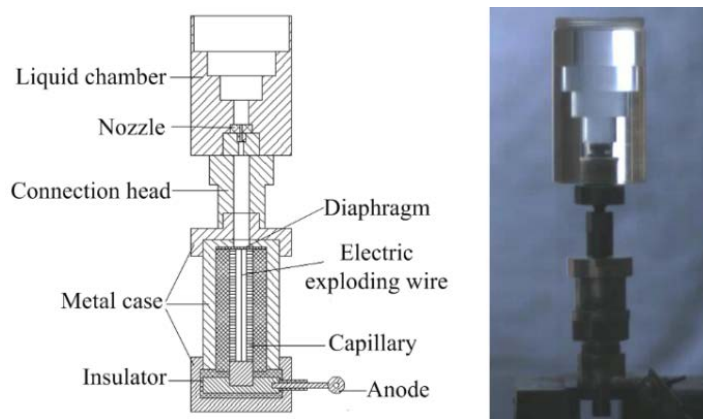


Figure 2. Plasma generator and liquid chamber.

The anode was sealed and the cathode was connected to the nozzle bottom of liquid chamber. This liquid chamber has four steps and the size details are shown in **Table 1**. Considering the experimental safety, water, which has a similar density and viscosity with the liquid propellant, was adopted as the liquid working medium in this experiment.

2.2. Experimental Result

During the experiment process, the pulse power source loaded electric energy between the anode and cathode of the plasma generator. The exploding wire in the plasma generator exploded, and the high-temperature metal plasma was generated. Then the metal plasma ablated the polyethylene on the capillary wall, and the plasma mixture is generated. When the pressure in the nozzle was high enough to break the copper film, the plasma jet was injected into the stepped-wall liquid chamber. The expansion process of a plasma jet in water, shown as **Figure 3**, was recorded by a FANSTCAM-ultima APX high-speed digital photographic system with 3000 frames per second.

A plasma cavity, called Taylor cavity, forms within the working fluid inside the liquid chamber. This cavity's axial expansion goes faster than its radial expansion as the plasma cavity expands along the step structure in the liquid chamber. These images show that the cavity boundary is blurred, especially at the later stage of the expansion process, because there is strong turbulent mixing

Table 1. Structure size of the liquid chamber.

Structure	Length/mm	Diameter/mm	Diameter Increment/mm
step1	20	18	/
step2	20	30	12
step3	20	42	12
step4	38	54	12

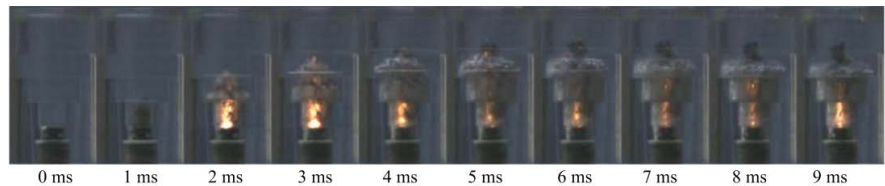


Figure 3. The expansion process of a plasma jet in the water.

of plasma and water at the interface. Further, this turbulence is stronger near the step corner than other areas, because the stepped-wall structure causes the reflow liquid which enhancing the plasma-liquid interaction at the step corner. In addition, the plasma cavity is brighter during the period of 2 - 4 milliseconds, indicating the thermal energy of the plasma jet is greater at this period. Certainly, the shading effect caused by many bubbles and vapors should be not ignored in these graphs.

3. Numerical Calculation

3.1. Theoretical Model

An unsteady 2D theoretical model was established to simulate the expansion process of a plasma jet in liquid. Some physical assumptions are made as follows:

- 1) The Volume of Fluid model calculates the multiphase flow and the Standard k-ε model simulates the plasma-liquid turbulent mixing.
- 2) The plasma-liquid interaction process studied in this work is short (not more than 10 milliseconds), so the liquid vaporization is ignored. The effect of the plasma sheath, as well as the effect of gravity, is also ignored to simplify the calculation.
- 3) The plasma jet is approximated as a high-temperature and high-pressure compressible fluid.

Based on the assumptions, governing equations are described as following:

- 1) Equation of continuity:

$$\frac{\partial(\alpha_q)}{\partial t} + \mathbf{u} \cdot \nabla \alpha_q = 0 \tag{1}$$

where \mathbf{u} is velocity, α_q is the volume fraction of q th phase. The volume fraction of the primary phase (plasma), α_1 , will be calculated based on the constraint: $\alpha_1 + \alpha_2 + \alpha_3 = 1$.

- 2) Momentum equation:

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot [\mu(\nabla \mathbf{u} + \nabla \mathbf{u}^T)] \quad (2)$$

where ρ is density, p is static pressure and μ is dynamic viscosity. \mathbf{u}^T is the transposed matrix of \mathbf{u} .

3) Energy equation:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\mathbf{u}(\rho E + p)) = \nabla \cdot (k_{\text{eff}} \nabla T) + S_h \quad (3)$$

where k_{eff} is effective thermal conductivity, E is energy and T is temperature. The radiant energy S_h is given by

$$S_h = f \sigma (T - T_0)^4 \quad (4)$$

where f is emissivity, σ is Stefan-Boltzmann constant and T_0 is environment temperature.

4) State equation:

$$p = \rho TR \quad (5)$$

where R is mixing gas constant.

5) Turbulence equation:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x}(\rho k u_x) = \frac{\partial}{\partial r}[(\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial k}{\partial r}] + G_k + G_b - \rho \varepsilon - Y_M \quad (6)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x}(\rho \varepsilon u_x) = \frac{\partial}{\partial r}[(\mu + \frac{\mu_t}{\sigma_\varepsilon}) \frac{\partial \varepsilon}{\partial r}] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (7)$$

where k is the turbulence kinetic energy, and ε is its dissipation rate, σ_k and σ_ε are the turbulent Prandtl numbers for k and ε . In the equation, $\mu_t = 0.09 \rho k^2 / \varepsilon$, $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are constants, x is axial displacement, r is radial displacement, u_x is axial velocity. G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to buoyancy, Y_M represents the contribution of the fluctuating dilatation during the compressible turbulence to the overall dissipation rate.

3.2. Calculation Domain and Mesh

The axial symmetry of the theoretical model enables the computational domain adopted half of the plasma-liquid interaction flow field. The computational domain, as shown in **Figure 4**, includes nozzle, liquid chamber, and atmospheric

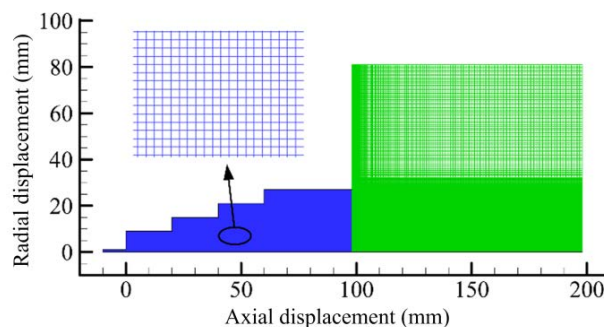


Figure 4. Calculation domain and mesh.

environment. The geometric size of the liquid chamber is the same as the liquid chamber in experimental devices. The nozzle is 10 mm in length and 1 mm in radius, and the atmospheric environment is 100 mm in length and 81 mm in radius.

The computational domain is divided into the rectangular grid, and the gradient mesh is adopted in the atmospheric environment to shorten calculation time. The mesh has 90 thousand cells, and mesh independence has been verified.

In the computational domain, the left exit of the nozzle is defined as the inlet boundary whose pressure is determined by the experiment, the temperature is 5000 K. The pressure outlet parameters are the same as atmospheric parameters. The no-slip heat insulation condition is adopted at the wall, and the standard wall function method is used near the wall to deal with turbulence. At the initial time, the plasma jet has not been ejected into the liquid chamber filled with water, so the pressure of the computational domain is 101,325 Pa and the temperature is 300 K.

4. Discussion and Results

Expansion process of a plasma jet in the stepped-wall liquid chamber filled with water was analyzed by the numerical calculation. The phase distribution of the plasma-water interaction flow field is shown as **Figure 5**. The plasma expansion characteristics agree well as the experimental results. A plasma cavity forms inside the stepped-wall liquid chamber, and its axial expansion goes faster than the radial expansion. A wavy interface is created by the plasma-liquid relative motion. When the inertial force acting upon the wavy interface exceeds the surface tension force, the crest of the surface wave is picked off into small droplets, which are entrained into the plasma cavity. There is strong plasma-liquid turbulence mixing at the interface. The radial induction effect of the stepped-wall structure enhances the radial expansion of the plasma jet.

We defined the maximum axial position where the plasma volume fraction is more than 90% as the axial penetration distance of plasma jet. The experimental and calculated time histories of the axial penetration distance of plasma jet are

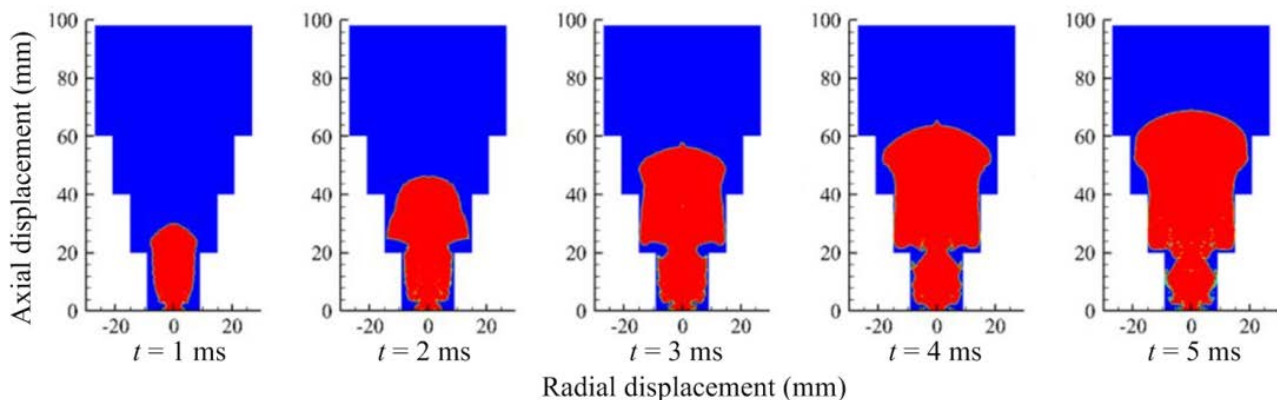


Figure 5. Phase distribution of the plasma-water interaction flow field.

shown in **Figure 6**. Those curves are in a good agreement, indicating the calculation model is reasonable in this work.

The pressure distribution of plasma-liquid interaction flow field is shown in **Figure 7**. With the plasma-liquid interaction, an arc-shaped pressure wave is generated at the front of the interface and then evolves into the plane wave by the reflection of the chamber wall. A high-pressure area forms at the head of the plasma jet, because the plasma jet has a great compression at the jet head area. This high-pressure area moves downstream and gradually decreases with the plasma expansion in liquid. When this high-pressure area moves near the stepped-wall structure, it expands towards the chamber wall due to the radial induction effect of the steps. At the later expansion stage, this high-pressure area disappears because there is a pressure balance between water and plasma jet at this time. Besides, there is a local low-pressure area at the corner of the step due to the influence of stepped-wall structure in the liquid chamber.

5. Conclusions

The evolution process of a plasma jet in the stepped-wall liquid chamber with four steps was observed by the experiment. Based on the experiment, a two-dimensional axisymmetric unsteady mathematical physics model of a plasma jet expanding in water was established to study the plasma-liquid interaction mechanism. The calculated results agree well with the experimental results. The conclusions are obtained as follows.

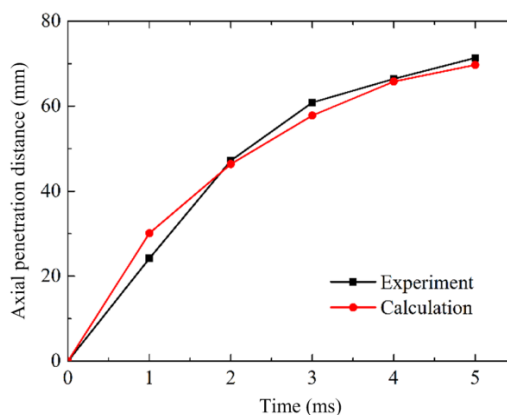


Figure 6. Axial penetration distance of plasma jet.

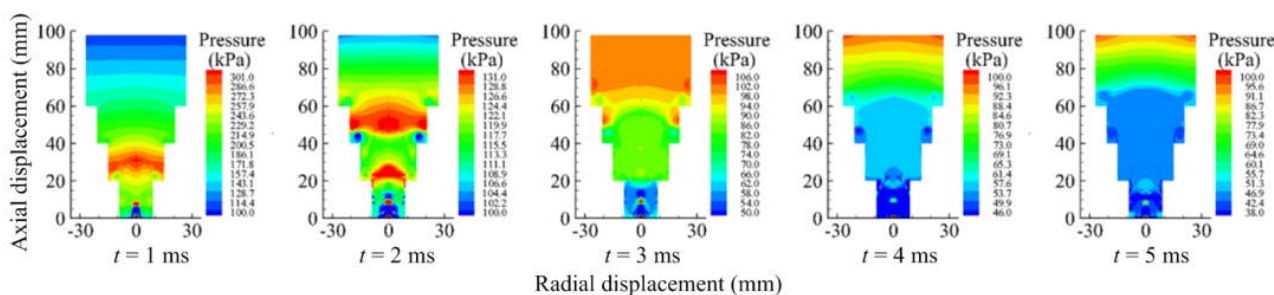


Figure 7. Pressure distribution of plasma-liquid interaction flow field.

1) As the plasma jet expands in water, a plasma cavity, which forms within the water inside the liquid chamber, expands along the stepped wall. This cavity's axial expansion goes faster than its radial expansion. The radial induction effect of the stepped-wall structure enhances the radial expansion of the plasma jet. The plasma cavity is brighter during the period of 2 - 4 milliseconds in the sampling period. Besides, there is strong plasma-liquid turbulent mixing at the interface, especially near the steps and nozzle exit.

2) The plasma-liquid interaction has an effect on the pressure distribution in the flow field. An arc-shaped pressure wave is generated at the front of the plasma jet and then evolves into the plane wave. A high-pressure area forms at the head of the plasma jet and then moves downstream. Besides, there is a local low-pressure area at the corner of the step.

Fund

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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