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Research Progress on Liquid Explosive Dispersion

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Abstract: Liquid explosive dispersal refers to the process in which the instantaneous high pressure generated by explosive detonation drives the liquid within the device. This paper reviews domestic and international research on liquid explosive dispersal, categorizing it into core directions including dispersal mechanism, influencing factors, and numerical simulation, and systematically summarizes the research progress of key parameters during the liquid explosive dispersal process.

Keywords: Simulant; Explosive dispersion; Numerical simulation

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1. Introduction

When an explosive detonates, it creates an instant high pressure that drives the liquid inside a device, this is the core of liquid explosive dispersion. Depending on the liquid's properties, it can serve specific functions; it's widely used in engineering and agricultural fields for tasks like fire suppression, explosion inhibition, pest elimination, and artificial rainfall [1–3]. Once the central explosive charge initiates, detonation products drive and spread the surrounding medium, kickstarting the dispersion process. This process is super-fast, dynamic, and involves messy, hard-to-track interactions between liquid, solid, and gas phases. It covers physicochemical phenomena such as shock wave and reflected wave interactions, causing structural failure, liquid interface disturbance, fragmentation, and phase change. A whole range of factors shape this process; areas based in explosion mechanics, solid mechanics, fluid dynamics, thermodynamics, chemical kinetics, and dynamic testing techniques seem to contribute to how it unfolds [4]. For this paper, I'm going to break down liquid explosive dispersion from four distinct perspectives.

Back in 1990, Gardner and Glass from Sandia National Laboratories split the liquid explosive dispersion process into 'near-field' and 'far-field' stages, sorting them based on which forces have the biggest effect on the liquid [5,6]. Detonation forces dominate the 'near-field' stage; aerodynamic drag forces take over in the 'far-field' stage. They used hydrodynamic methods to run numerical simulations and analyzed key characteristics of both stages; this was the first full look at the entire liquid explosive dispersion process. This relatively simple classification seems to have been widely adopted in later research. Research in the area dates back to the 1960s in the USA, though. Poppoff et al. divided the explosive dispersion process into four stages, basing their work on phenomena they actually observed: detonation, shock, separation, and jetting [7]. Samirant et al. used flash X-ray photography to capture images of the liquid explosive dispersion process, and these shots revealed a liquid ring formed when expanding detonation product gases pushed the liquid fill outward [8]. Also, Zabelka et al. took photos that showed another dispersion pattern, jets spraying radially outward from the explosion center [9].

2. Method and design

2.1. Research on liquid explosive dispersion mechanisms

2.1.1. Primary fragmentation

Primary fragmentation is the first stage when dispersed liquid starts breaking apart; it marks the beginning of the whole atomization process. It decides the motion range of the liquid and gives secondary fragmentation its initial conditions. When we want to study this initial stage of fragmentation, Linear instability theory seems to be the primary theoretical approach we rely on.

When the interface between liquid and gas gets unstable and keeps getting worse, it will eventually make the liquid break apart, this is the initial stage of liquid explosive dispersion that Yue Zhongwen calls primary fragmentation. This is how the explosive starts to spread; it may happen quicker than we expect [10]. Then, common instabilities include [11].

Let me kick off with Rayleigh-Taylor (R-T) instability; it arises from interface instability between two fluids of different densities when gravity and inertial forces act on them.

Kelvin-Helmholtz (K-H) instability is the second phenomenon I talked about. It comes up when two fluids have a tangential velocity difference; interface perturbation starts to develop as a direct outcome of that side-to-side speed difference between them.

Richtmyer-Meshkov (R-M) instability is the phenomenon we're talking about. When a shock wave transmits through a fluid interface, it imparts a finite acceleration to the interface; this then sets off perturbation growth.

Yang Lei et al. did experimental research on axisymmetric dispersion of glycerol; they used a modified vertical shock tube to carry out their tests [12]. When they went through all the data collected from these experiments, they found some key results that may help us understand how glycerol disperses in that axisymmetric setup.

We ran experiments with transparent glycerol; we could actually watch how R-T and R-M instabilities develop step by step throughout the entire process of axisymmetric dispersion. We captured clear images of bubble and spike growth. By going through these images, we can tell that this growth in the mixing region may lead to primary fragmentation.

So when we ramp up driving force and shock Mach number, it seems to affect the unstable interface in two ways. The initial perturbation wavelength gets shorter; the wavenumber goes up.

We cranked up the driving force, and spike growth picked up really fast. Location of primary fragmentation didn't shift at all. K-H instability and surface tension seemed to have a stronger influence on the spikes; this made spike fragmentation far more intense than before.

2.1.2. Secondary fragmentation

Secondary fragmentation of droplets is a crucial stage in liquid dispersion. In this stage, droplets formed during primary fragmentation undergo further breakup under aerodynamic forces. The main research methods include phenomenological analysis and linear instability theory.

Hinze's research showed that the mode of secondary fragmentation is determined by two dimensionless numbers composed of three forces: the Weber number (We) and the Ohnesorge number (Oh) [13].

The Weber number (We) is the ratio of inertial force (drag) to surface tension force:

$$We = \frac{\rho_e d_l v^2}{\sigma_l} \quad (1)$$

Where ρ_e is the ambient gas density, d_l is the droplet diameter, v is the droplet velocity, and σ_l is the surface tension coefficient.

The Ohnesorge number (Oh) is the ratio of viscous force to surface tension force:

$$Oh = \frac{\mu_l}{(\rho_l d_l \sigma_l)^{\frac{1}{2}}} 7 \quad (2)$$

Where μ_l is the dynamic viscosity coefficient of the liquid.

Yang Wei et al. used the CLSVOF multiphase flow model coupled with adaptive mesh refinement to study the transition mechanism between different droplet breakup modes [14]. Their research indicated that R-T instability plays a significant role in the transition of droplet breakup modes. The ratio of the droplet's maximum diameter to the maximum R-T unstable wavelength directly influences the droplet breakup mode.

Wang Chao et al. conducted experimental and numerical simulation studies on the breakup process of droplets under incident shock waves [15]. They analyzed droplet deformation and breakup using We and Oh numbers. Analysis of experimental and simulation results showed that increasing We promotes droplet breakup. Beyond a certain We value, droplet breakup transitions from shear breakup to catastrophic breakup.

2.2. Numerical simulation research on liquid explosive dispersion

Shi Yina et al. used a dimensionally split Eulerian program coupled with the Youngs' interface treatment method to simulate the liquid stratification phenomenon in the flow field of glycerol and water media driven by a central explosive charge [16]. Combined with experimental results, they proposed three coexisting mechanisms during droplet formation: fragmentation of the outer jet, R-T instability in the inner layer, and "cavitation" fragmentation in the intermediate liquid layer.

Measuring the concentration of explosive materials post-dispersion is challenging. Numerical simulation offers a solution; however, existing models for calculating particle concentration often neglect measuring initial particle conditions, leading to inaccuracies in describing concentration distributions. Chen et al. proposed a model to predict the concentration distribution of dispersed liquid and particulate materials after an explosion, which was validated and showed good agreement with experimental data [17].

2.3. Research on factors influencing liquid explosive dispersion

2.3.1. Influence of explosive energy

(1) Effect of charge mass

Wu Deyi et al. conducted dispersion experiments with water and alcohol under different specific charge masses (charge mass per unit liquid mass) under identical conditions [18]. Results showed that increasing the charge mass significantly increases the initial dispersion velocity of the liquid. Simultaneously, the velocity attenuation coefficient increases, the dispersion duration decreases, and the dispersion radius increases. Yan Shilong et al. concluded from water explosion experiments with varying specific charge masses that larger specific charge masses result in more uniform water fragmentation, better continuity of the water mist, and a relatively uniform overall mist concentration [19]. Tang Hui, based on energy conservation and detonation principles and introducing a correction coefficient ‘k’ and ‘ω’, proposed a method for calculating dispersion parameters:

initial liquid velocity:

$$v1 = \sqrt{\frac{4 m_e Q_v \left[1 - \left(\frac{r_0}{r_1}\right)^4\right]}{k^2 m_e + 2 m_1 + 2 k^2 m_s}} \tag{3}$$

Where: r_0 is the initial radius of the shell; r_1 is the rupture radius of the shell; m_1 is the mass of the liquid filling; ms is the mass of the warhead shell; me is the mass of the central explosive tube; Qv is the explosive heat of the explosive; k is the correction coefficient (taken as 0.3 according to the results of previous tests).

Throwing radius:

$$R = r_0 + \frac{v_1}{\omega} \tag{4}$$

Where: ω is a correction coefficient (fitted from static explosion results, taken as 32)

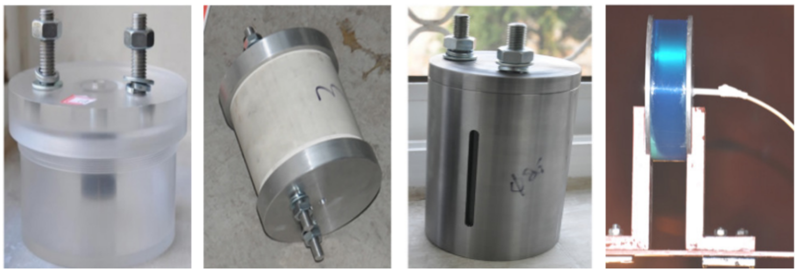
Comparison of calculated and measured values showed maximum relative errors of 18.8% for initial velocity and 17.6% for dispersion radius, both meeting error control requirements. Experiments also showed that both the initial velocity and dispersion radius of liquid fire suppressant are proportional to the central explosive charge mass.

(2) Effect of energy distribution

Experiments showed significant differences in fuel dispersion velocity at different positions for Structure A, with velocity at the small end notably higher than at the large end. Structure B formed an approximately cylindrical cloud initially, with no significant difference in fuel diameter between large and small ends. Dispersion velocity differences across positions in Structure B were also smaller, with the maximum velocity at the small end slightly higher than at the large end. It can be concluded that the fuel dispersion velocity at different positions of the truncated cone device is related to the charge mass per cross-section, with initial velocity increasing with charge mass. Based on extensive experiments and analysis with different liquids, scholars concluded that for liquid explosive dispersion, the initial cloud velocity and dispersion radius are linearly related to the charge mass, but this relationship changes beyond a certain point.

2.3.2. Influence of device structure

Lu Xiaoxia et al. conducted liquid explosive dispersion experiments with different casing materials (PMMA, PVC, Steel, Film - **Figure 1**) [20]. They found that under the action of reflected rarefaction waves, liquid cavitation occurs. Higher casing strength delays cavitation onset and shifts its location closer to the explosion center. Furthermore, mixing between detonation product gases and the liquid occurs earlier near their interface with stronger casings.



(a) PMMA (b) PVC (c) steel (d) Film

Figure 1. Explosive dispersion devices with different casing materials.

2.4. Droplet size measurement

The Sauter Mean Diameter (SMD or D32) is a widely used parameter in multiphase systems to describe the average particle size of droplets or particulate groups. Cai Qingjun et al. utilized an optical method based on Dobbins' laser scattering principle to measure the spatial and temporal distribution of the SMD of droplets formed during the secondary fragmentation of axisymmetric liquid dispersion [21]. The experimental setup is shown in **Figure 2**.

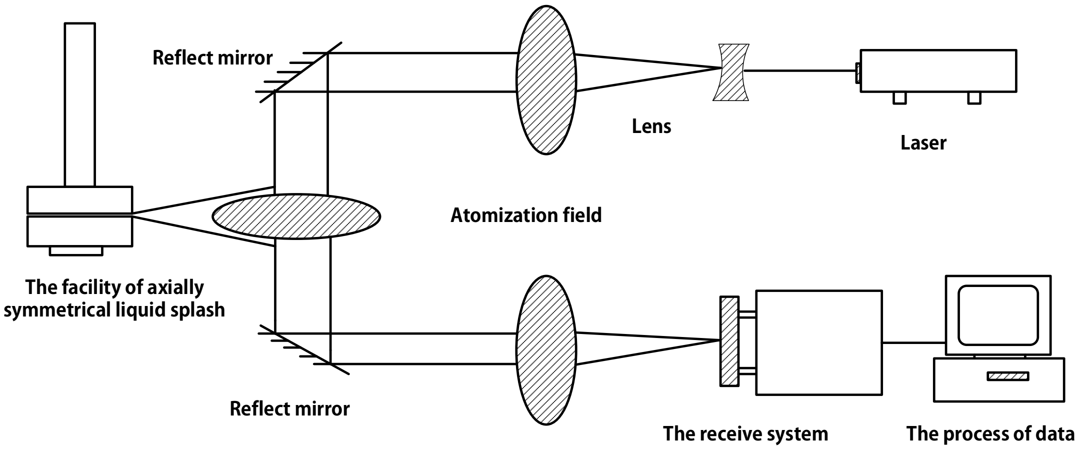


Figure 2. Optical path for measuring particle size from secondary fragmentation in axisymmetric horizontal liquid dispersion.

As shown in **Figure 2**, the setup uses a U-shaped container and a diaphragmless shock tube to achieve axisymmetric liquid ring dispersion and atomization. A laser beam is generated, reflected twice, and focused onto a receiver. A computer processes the acquired data to obtain the SMD of secondary fragmented droplets. System calibration confirmed the reliability and accuracy of this optical measurement system for determining the size of aerosol clouds generated by axisymmetric liquid dispersion.

3. Results and discussion

This paper discusses the dispersion of liquid explosions from three perspectives: the dispersion mechanism of liquid explosions, the factors influencing the dispersion of liquid explosions, and numerical simulation of the dispersion of liquid explosions.

Research on the dispersion and fragmentation mechanism of liquid explosions primarily employs linear instability theory as the main research method, dividing the entire process of liquid explosion dispersion into initial fragmentation and secondary fragmentation. Therefore, in subsequent research, the classification of these two dispersion stages can be further refined or alternative classification methods can be explored.

Regarding the numerical simulation of explosion dispersion, scholars both domestically and internationally typically employ a staged approach, simulating the near-field and far-field stages using different models. To more accurately simulate the various stages of liquid explosion dispersion, future simulations could explore alternative models and compare them with existing models to identify the optimal model under different conditions.

Research on the influencing factors of explosion dispersion is conducted by varying the explosion energy and dispersion devices. Explosion energy includes the effects of charge quantity and energy distribution on dispersion efficiency. Scholars have conducted experiments with different explosion energies and dispersion devices, concluding that under appropriate conditions, a larger charge quantity leads to better dispersion efficiency; different dispersion devices yield different dispersion efficiencies, so appropriate devices should be selected based on specific scenarios in practical applications.

4. Conclusions

Right now, when we focus on multiphase coupling models and high-precision measurements, current research still has some noticeable shortcomings; it may not cover all the little details we need to get accurate results.

Let me start with model limitations: current staged models can't describe the multiphase coupling effects of turbulence-fracturing-phase transition. They may only handle each process on its own. To some extent, they focus on single-phase behaviors, completely missing how turbulence, fracturing, and phase transition interact in a multiphase system.

We face a technical bottleneck right now. In situ measurements of nanoscale droplets don't have enough precision; we need to work on improving that to get more accurate, usable data for our thesis.

Next, for future developments, we can focus on intelligent optimization algorithms based on machine learning; we'll pair these with microfluidic experiments to reveal fragmentation mechanisms at submillimeter scale, and this may drive dispersion devices toward better controllability and higher efficiency.

Disclosure statement

The authors declare no conflict of interest.

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