The mechanism of propulsion effect of BLEVE based on discharge

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Abstract. Propellant could reach a high pressure and temperature situation in a very short time by the use of high voltage pulsed discharge. Once sharp depressurization occurs, BLEVE (boiling liquid expanding vapor explosion) happens immediately with a violent phase transition. A two-phase flow with high pressure and speed forms and often causes severe damage. It is also useful in other aspects such as propulsion. The numerical simulation of BLEVE for propulsion shows the pressure has a sharp increasing when phase transition begins. Then a two phase mixture flow moves forward with a high speed and compresses the gas in front.

1. Introduction
Since the sixties of last century, electric propulsion has been applied in areas such as aeronautics and astronautics. Traditional propellants mainly contain Teflon, xenon, mercury, etc. These propellants may lead to plume contamination. Several researchers try to find other alternative propellants. As we know, water is non-polluting and non-corrosive. It has higher specific impulse and larger explosion volume ratio [1-4]. Considering water is relatively ideal explosion propellant, it is a new attempt to use BLEVE as propulsion power. The BLEVE is a type of physical explosion and has been defined as an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point to local pressure. There are a lot of experiments and theory researches about the process of BLEVE. But there is no accurate model which could describe the whole process. The high energy two-phase flow may have severe damage. But finding a way to use it is also valuable. In this paper, 2D numerical simulation is carried out as a preliminary exploration for the use of BLEVE.

The traditional external heat conduction is slow and non-uniform. The propellant could be directly discharged by a high-power pulsed power source [5, 6]. By the control of external conditions (i.e. voltage, charge power), the propellant could be heated up to 523 K or higher.

2. Model design
2.1 two-phase flow model
Actually the BLEVE is a process of violent phase transition. When depressurization occurs in liquid, the superheat situation leads to a violent phase transition from liquid to vapor and a large number of bubbles form in liquid. Energy transfer on the bubble surface makes bubble grow rapidly and two-phase mixture flow forms. The violent vapor generation causes rapid surge of the two-phase flow.

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mixture volume. This condition will increase the internal pressure. When bubbles burst, energy is released and this will contribute to the increase of pressure too. The high pressure has a propulsion effect on surroundings.

The physical model of two-phase flow is assumed incompressible. The momentum equation is [7]:

$$\frac{\partial}{\partial t} (\rho \vec{u}) + (\nabla \cdot (\rho \vec{u}) \otimes \vec{u}) = -\nabla p + \rho \vec{g} + \nabla \mu [(\nabla \cdot \vec{u}) + (\nabla \vec{u})^T] + 2\sigma \kappa \delta_S \vec{n}$$

where \(\vec{u}, \rho, \mu, p, \vec{g}\) denote velocity, density, dynamic viscosity, pressure, volume force (gravity). \(\sigma\) is surface tension. \(\kappa\) is local interface curvature. \(\delta_S\) is Dirac function on the interface of \(S\). \(\vec{n}\) is normal vector of interface. The energy and continuity equations are:

$$\rho C_p \frac{dT}{dt} + \vec{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + \Phi$$

$$\nabla \cdot \vec{u} = \Gamma$$

Here the viscous dissipation in energy equation is neglected. \(T, C_p, k\) denote temperature, heat at constant pressure, thermal conductivity and \(\Phi\) is latent heat energy source that comes from the phase transition on interface. \(\Gamma\) is the volume change caused by mass transfer on the interface between different phases.

![Figure 1. Propulsion model.](image)

The phase transition rate is unsteady for the influence of some complex factors such as pressure, temperature and bubble generation. It is difficult to find a model to predict the rate accurately [8, 9]. Figure 1 shows the initial design of the propulsion model. The length and diameter of column vessel is 200 mm and 100 mm, which connect with a long barrel. The length of barrel is about 1000 mm with diameter of 20 mm. The bullet for propulsion is about 15 g. About one third of the vessel is filled with water.

2.2 Discharge model

By the way of high voltage pulsed discharge, we can make the water reach experimental temperature in a short time. In general the discharge includes corona discharge and arc discharge. When corona discharge occurs, plasma only generate around electrodes. Arc discharge requires more energy and plasma channel appears through electrodes. In general the charge and discharge process could be described by an equivalent circuit. The equivalent circuit is shown in figure 2.

The characteristic of discharge in water is determined by differential equation of RLC circuit as:

$$L \frac{d^2Q}{dt^2} + R(t) \frac{dQ}{dt} + \frac{Q}{C} = 0$$

Here \(L\) and \(C\) are inductance and capacitance. \(Q\) is the stored charge and \(R(t)\) is the impedance mainly determined by the discharge channel.

The shape of electrode could be used is various (i.e. sphere-ring electrode) [10]. When discharge happens, the energy released from capacitance is divided into several parts such as circuit equivalent
resistance, water energy, shock wave energy, radiation energy etc [11].

![Equivalent circuit](image)

**Figure 2.** Equivalent circuit.

3. **Numerical simulation method**

Strictly speaking, phase transition happens after the spread of rarefaction wave in liquid. So it happens on the surface first. We assume that depressurization in liquid phase has finished so quickly that we can neglect it because the area of propellant is narrow. When the simulation starts, the phase transition occurs at once in the whole liquid.

At the beginning, the water has reached saturation condition of 523 K with pressure of approximate 3.9 MPa by the use of pulsed discharge. Triangle mesh and finite volume method is adopted. PISO (pressure implicit with splitting of operators) algorithm that is one of the pressure based schemes is used for pressure-velocity coupling. For spatial discretization, PRESTO (Pressure Staggering Option) is used for pressure terms and first order upwind is used for other terms such as volume fraction, energy, etc. The boundary conditions of wall are no slip and adiabatic. In the flow field, the relation between temperature and corresponding evaporation pressure can be obtained by Antoine equation. If the evaporation pressure is larger than local pressure, the mass transfer happens from liquid to gas. If the evaporation pressure is smaller than local pressure, the transfer happens in the opposite direction. Triangle mesh is used and the simulation stops when bullet move to the end of the barrel.

4. **Flow field parameters analysis**

4.1 **pressure of monitoring point**

![Pressure of monitoring point](image)

**Figure 3.** The pressure of monitoring point.
A monitoring point is set in the center of water area, so that we can record the change of pressure. Figure 3 shows pressure change of the point in initial iteration of about 1000 time steps. Each step equals 10⁻⁶ s. When the calculation starts, depressurization accomplishes in a very short time. Then phase transition occurs in the whole liquid. The liquid phase’s pressure increases suddenly because of violent evaporation. Internal pressure could rise to 3 or 4 times higher compared to the initial saturated pressure. Then a high speed two-phase mixture fluid erupts and impresses the gas in front. As the volume expands rapidly, pressure will decrease with timing process. So the flow field pressure is determined by both evaporation and expansion.

4.2 instantaneous flow field parameters

Figure 4 shows the vessel’s internal states at about 1.5 ms. We consider the initial gas in air zone (shown in figure 1) as ideal gas, so the ideal gas equation is suitable for the compressed gas. When the gas is blocked by the front wall, the speed will slow down and both pressure and temperature rise up. As the evaporation pressure is higher than actual pressure in the whole field, there is no transition from gas to liquid. As shown in the third and fourth figures, the front speed of mixture flow is expanding rapidly with the speed of about 100 m s⁻¹ at this moment. Mixture flow compresses front gas and the gas push bullet forward.

![Figure 4. Pressure, temperature, velocity and density of flow field at 1.5 ms.](image)

4.3 bullet velocity and tail pressure

The acceleration of bullet is mutative in the whole calculation process. The drag force increases when bullet speeds up. The final velocity keeps around 350 m s⁻¹. This indicates the forces role in bullet has come to a balance condition. Tail pressure curve is no larger than 500000 Pa, this may be a little small compared to the mixture flow pressure for the reason that the two-phase mixture flow just compresses the gas in front and the direct force that pushes bullet comes from the compressed gas. As a part of gas flow out through the gap between bullet and barrel, the tail pressure increases to about 500000 Pa and then decreases. At about 4 ms, as reflected shock wave reaches again, the tail pressure have a slightly ascension.
5. Conclusions

Through the simulation, we could get some important flow parameters. The pressure increases several times compared to initial field pressure when phase transition begins. The propulsion effect of BLEVE is obvious for the violent two-phase mixture flow. As the shock wave has a repeated oscillation in vessel, this could disturb the propulsion and lead to energy loss. The BLEVE may have a better application prospect on propulsion area by further researches, such as fixing the model, improving simulation algorithm, carrying out more experiments and discussing its propulsion efficiency.

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References

[1] Mao G W, Han X W, Yang J and He H Q 2000 Journal of Propulsion technology (in Chinese). 21 1
[2] Yang L, Li Z R, Yin L, Wu J J, Zhou J 2006 Journal of Rocket propulsion (in Chinese). 32 32
[3] Scharlemann C A 2003 Investigation of thruster mechanisms in a water fed pulsed plasma thruster (UMI number: 3119256)
[4] Li J, Cao Y D, Yu L B and Yuan D S 2008 Journal of Shenyang university of technology (in Chinese). 30 498
[5] Liu X C, Feng C G, Zhu Z L, Xu Y Z and Xu Z 1999 Journal of Beijing institute of technology (in Chinese). 19 8
[6] Lu X P, Zhang H H, Pan Y, Liu K F and Liu M H 2001 Explosion and shock waves. Explosion and shock waves (in Chinese). 21 282
[7] Yuan M H, Yang Y H, Li T S and Hu Z H 2007 J. Eng. Thermophys. 28 962
[8] Chen S N, Sun J H and Wan W 2008 J. Hazard. Mater. 156 530
[9] Pinhasi G A, Ullmann A and Dayan A 2007 Int. J. Heat Mass Transfer 50 4780
[10] Zhu T Y, Wan X H, Zhang Q G and Yang L J 2008 Journal of xi’an jiantong university (in Chinese). 42 723
[11] Li N, Huang J G, Chen J F, Lei K Z and Zhang Q F 2010 Journal of basic science and engineering(in Chinese). 18 1010

Figure 5. Velocity and tail pressure of bullet.