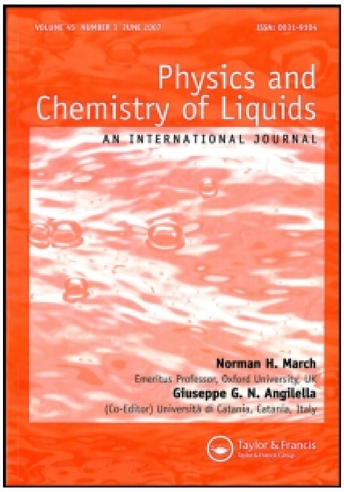

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CRATER FORMING PROCESS BY LIQUID DROP IMPACTING LIQUID MULTI-LAYER TARGET

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In this article, the experiment of the impacting by liquid drops against liquid multi-layer target was carried out. From the results, a theoretical analysis was made to study the principle of the crater forming process. The crater was formed only in the first layer of the liquid target within certain impacting energy. The interface energy was one of the important parameter of crater forming process if there were dissolution phenomena between the liquid multi-layers. According to energy conversation and the analysis of the impacting energy transformation, the equation of the cavity diameters was obtained. It was found that the results of experiment agreed with that of theoretical analysis very well. The results of simulating experiments predicted that using the metal multi-layers construction would enhance the protection capability, which can be used as the reference for protection design of aircrafts.

Keywords: Liquid drop; Liquid multi-layer target; Crater process; Equation of the cavity diameters

1 INTRODUCTION

It is well known that the threat of space debris and micro-meteors to the safety of spacecrafts is serious because the impacting velocity is of the order of kilometers per second. According to estimates, most space debris are metal materials which can be compressed, melted and boiled because of the serious impacting at the impacting spot. Öpik [1] noted that the metal impacting process was similar to liquid impacting process and the impacting simulation was valuable to study the crater forming process.

In the end of 19th century, Worthington studied the process of liquid drop impacting liquid target. In 1966, Engel carried out an experiment on liquid drop impacting liquid target, described the crater forming process and gave crater diameter equation [2]. In 1980, Lukashev studied solid pill impacting target by liquid simulation experiment on the basis of similarity theory and dimensional analysis [3].

In this article, experimental analysis was made to determine the effect of the thickness of liquid layers and velocity of liquid drops on the crater formation process. The results

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of the experiment indicated some characteristics of the crater formation. From the results, the equation of crater diameter for multi-layers target was obtained, which had been identified by experimental data.

2 EXPERIMENT OF LIQUID DROP STRIKING MULTI-LAYER LIQUID TARGET

2.1 Experimental Apparatus

The main elements of apparatus for hydro-simulation dense multi-layer protective structure test are shown in Fig. 1. The maximum shooting speed of hypervelocity camera is 4000 pictures/s, and 30 m long films are used. The average shooting time is 2–4 s. The counter flashes 1000 time/s, the film records flashes, and the shot speed can be calculated according to flash marks. Reference mash separated at spacing of 5 mm is printed on the paper pasted on the back of liquid tank. The light of 2 kW focus lamp pass through the parchment paper with the reference mash and get to the film. So, the crater forming process can be observed very clearly. The data of velocity of the droplet, crater diameter and crater depth can be got from the film through the scale compare method.

Three kinds of mutually insoluble liquid (slight soluble) were used as the liquid target in the dense multi-layer protective structure test. The three kinds of liquid are seed oil, water and glycerin, which form three liquid layers from top to bottom according to the different density (cocktail). The droplet is water drop and its average mass is 0.0454 g, diameter is 0.442 cm, the density of seed oil is 0.8884 g/cm^3.

2.2 Analysis of Experiments

The crater formation process can be know by using high speed camera. A column coordinate was introduced where r and h axis were parallel and vertical with free surface of liquid target respectively. From the photographs, a phenomenon was seen that at first there was no obvious change on free surface of liquid target after all liquid

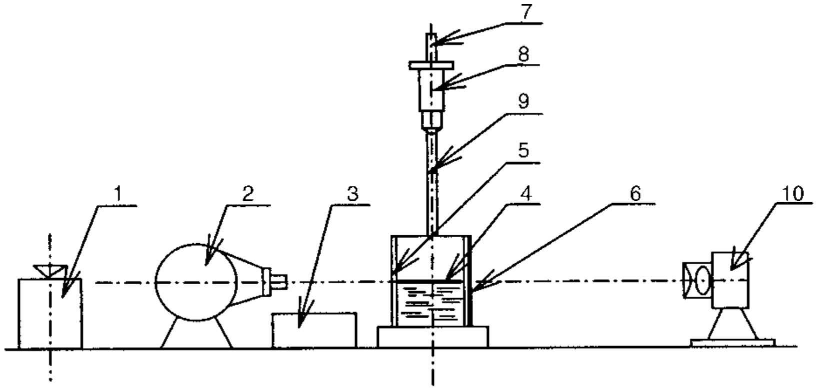
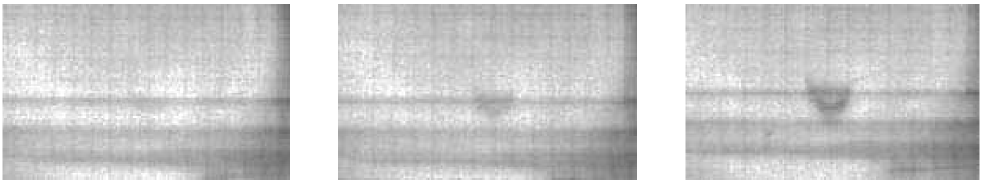
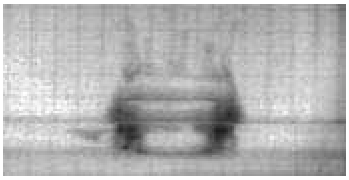


FIGURE 1 Sketch of the experimental apparatus: 1 – power; 2 – hypervelocity camera; 3 – counter; 4 – tank which contains the test liquid; 5,6 – reference mash; 7 – holder of liquid drop facility; 8 – liquid drop facility; 9 – droplet; 10 – light source.



a 2 10^{-3}s after impacting b 4.6 10^{-3} s after impacting c 6 10^{-3} s after impacting



d 25.6 10^{-3}s after impacting

FIGURE 2 The forming process of crater by liquid drops impacting liquid multi-layers target.

drops invaded liquid target, which lasted from preliminary time to 10^{-3} or 3×10^{-3} s (see Fig. 2a), then a elliptical crater, whose long axis was parallel with *r* axis, appeared on free surface of liquid target. The tangent direction of the crater moved intensely in the preliminary moment of forming crate (see Fig. 2b). In the succedent process, the velocity of vertical direction increased and the figure of crater became approximate half ball (see Fig. 2c). The cricoid splashing wave appeared while the crater was forming in the instance of higher impacting velocity of liquid drops and lower viscosity of liquid target. Because of the influence of liquid surface energy and dissolution between liquid drop and liquid target, in the instance of preliminary time of impact, the splashing wave was composed of inside splashing wave and outside splashing wave. Inside splashing wave was composed of materials of liquid drops and outside splashing wave is composed of materials of liquid target. Inside and outside splashing wave arrived the culmination at the same time and contacted each other at the peak (see Fig. 2d). With increasing impacting velocity, the size of crater became larger and inside cavity was more clear. From 18×10^{-3} to 25×10^{-3} s after impacting, the velocity of liquid drop at vertical direction was zero, and the altitudes of inside and outside splashing waves were maximum, the diameter of crater was also maximum because all the kinetic energy of dropping liquid changed into potential energy of liquid target. The dark strip at the edge of crater appeared because some light was refracted by the surface of crater and cannot enter the lens of camera. The cricoid splashing liquid, which was formed on the top of crater, closed with the decreasing of inside pressure of crater and congregated to form liquid column which impacted liquid target again because of gravity. The size of crater depended on the impacting energy of liquid drop. The surface of liquid target came back the plane shape because of hydrodynamic effect and surface tension.

The crater forming process was studied by two experiments. The first was that both the botanic oil and water layers were 5 mm thick while glycerol layer was half infinite body (see Fig. 3). The second was that both the botanic oil and water layers were 2 mm thick while glycerol layer was half infinite body (see Fig. 4). The shooting speed in the first experiment was 2500 frame/s while that in the second experiment was 1500 frame/s. In two experiments, the water drops fell freely from 1.5 m height and the velocity of drops was 5420 mm/s when they arrived the surface of liquid target.

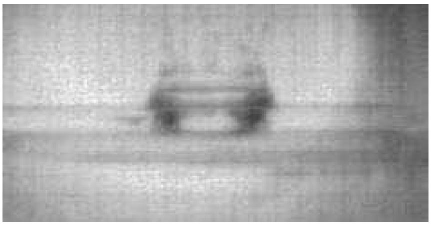


FIGURE 3 Crater shape with 5 mm liquid layer.

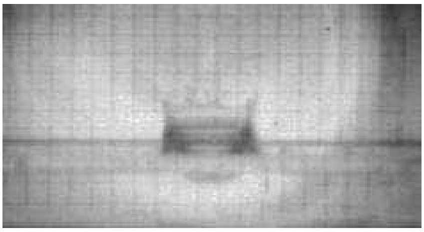


FIGURE 4 Crater shape with 2 mm liquid layer.

From the first experiment, when liquid drop impacted liquid target, liquid drop did not pierce the first layer of liquid target where the elliptical crater (almost cylindrical shape) was formed. The second layer was influenced very slightly by this process while the third one was hardly influenced. The layers of oil and water were reduced to 2 mm thick (the total thickness of oil and water was less than that of one layer in the first experiment) in the second experiment in order to test whether the results of first experiment were related to the impacting energy or not. Liquid drop did also not pierce the first layer of liquid target and the other two layers of liquid target were hardly influenced, which was similar to results in the first experiment. All the phenomena indicated that if impacting energy was small, the impacting crater only appeared in the first layer and other ones were hardly influenced no mater how thick the liquid layer was because of the interface energy between the layers.

From the results of the experiments, the maximal thickness of the crater was about the thickness of the first layer of liquid target and the maximal diameter was the main parameter needed to study.

2.3 Experimental Results

The above special phenomena were brought out when liquid drops impacted liquid multi-layers target because of the interface energy from the results in the two experiments. When the liquid column reached the highest point and the velocities at axis and tangent directions were zero, the maximal diameter crater was formed (see Figs. 4 and 5).

On the basis of the first and second experiments and the same experimental condition, the impacting experiments was accomplished with 2, 5 and 8 mm liquid layers and the 600, 900, 1200 and 1500 mm falling heights respectively.

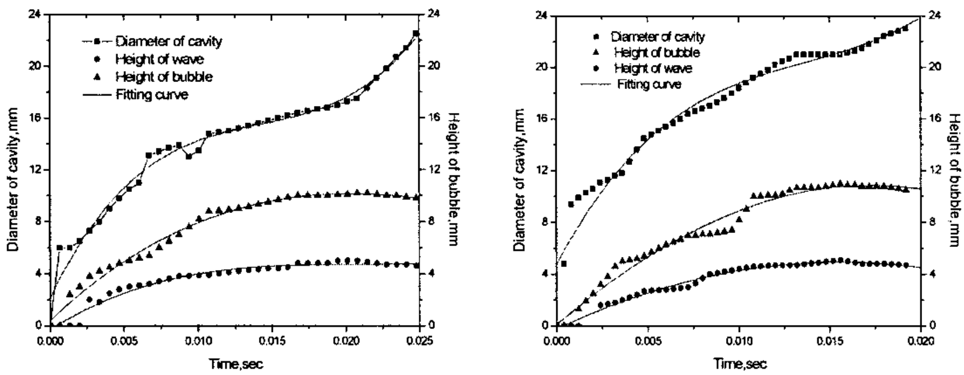


FIGURE 5 The curve of the diameter of crater and height of liquid column via time with: (a) 5 mm liquid layer; (b) 2 mm liquid layered.

3 THEORETIC ANALYSIS

3.1 Analysis of Crate Forming Process

The theory of liquid interface energy was used to explain the above experimental results. There were interfaces existing between air and liquid target, and between liquid layers. The interface energy between liquid layers of non-dissolution each other was higher than that of dissolution each other. The interface energy should be overcome in order to destroy these interfaces. On the common instance, the impacting energy was higher than the interface energy. However, if the energy needed to form the crater in the first liquid target was less than the interface energy between layers of liquid target, liquid drops flowed along with interfaces between liquid layers and cannot pierce the interface between the first and the second layers of the liquid target. The interface energy between liquid oil and air measured 32.736 mN/m at 20°C with capillary liquid ascent experiment.

The interface energy can be expressed by the following equation [4,5],

$$\gamma = (\partial F^s / \partial A)_T n_i^s$$

where r is the interface tension or interface energy, n_i^s is the molar number of matter i on the surface (s), F is the Helmholtz free energy, A is the the interface area and T is the temperature.

The interface energy of liquid metal was higher than that of liquid at room temperature. On the instance of the high velocity impacting, the crater forming process was influenced greatly by the interface energy of liquid metal.

3.2 Analysis of Impacting Energy

When the kinetic energy of liquid drops was transformed into the potential energy of liquid target, there was a crater with the maximum diameter. The maximal diameter of the crater can be derived from the law of energy conservation. Most of the kinetic energy of liquid drops was transformed into gravity and surface potential energy of liquid target.

3.2.1 Gravity Potential Energy

When the crater was formed, gravity potential energy (U) was transformed to produce and raise the internal and external liquid column from initial liquid surface. Gravity potential energy (U) is

$$U = g\rho_t \iint h \cdot 2\pi r \, dr \, dh \tag{1}$$

where G is gravity acceleration, ρ_t is the density of the top liquid, r is the distance along r axial (shown in Fig. 6). In the crater along r axial, r is from 0 to a, where a is the radius of the short axis of ellipse. Along normal direction, h is from $-a$ to 0, where h is the distance from the top of initial liquid surface to the impacted liquid surface. In the liquid column along r axial, r is from a to ∞. Along normal direction, h is from 0 to ∞. For obtaining potential energy (U), expression about liquid crater and liquid column needed to be deduced.

The shape of the wall of impacting crater is ellipse,

$$r^2 = a^2\left(1 - \frac{h^2}{b^2}\right) \tag{2}$$

The part of gravity potential energy of crater (U_1) by substituting (2) into (1) is

$$U_1 = 2\pi\rho_t g \int_{-\delta}^{0} \int_{0}^{\sqrt{a^2(1-h^2/b^2)}} r \, dr \, dh = \pi\rho_t g a^2\left(\frac{\delta^2}{2} - \frac{\delta^4}{4b^2}\right) \tag{3}$$

where δ is the thickness of liquid layer.

The height of liquid column is decided by two conditions. The former condition is that the volume of outside liquid column equals to the cubage of the crater, while

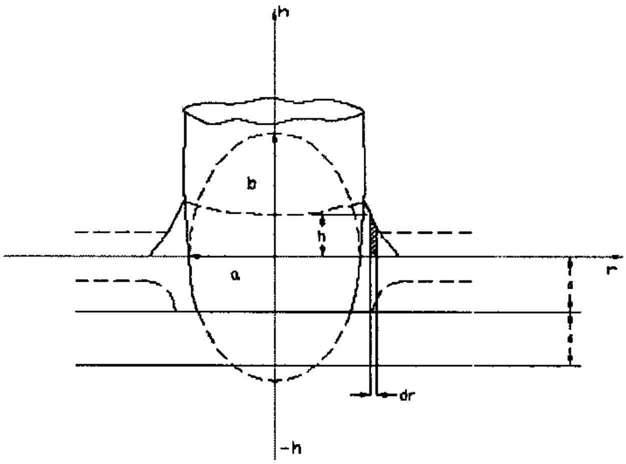


FIGURE 6 Scheme of impacting multi-layers liquid target.

the latter one is that the height of inside liquid column is 0 in infinite distance. From the former condition, we can obtain

$$2\pi \int_a^{+\infty} hr\,dr = \pi a^2\left(\delta - \frac{\delta^3}{3b^2}\right)$$

where h is expressed by the following equation.

$$h = -\frac{3b^2a^3\delta - a^3\delta^3}{6r^3b^2} \tag{4}$$

From the experimental results, the height of outside liquid column h is from $r = a \sim 2a$, and when r tend to ∞, $h = 0$. If h is constant, Eq. (1) can be written as,

$$U = \pi g \rho_t h^2 \int r\,dr$$

The potential energy of external liquid column can be obtained by substituting (4) into (1)

$$U_2 = \pi\rho_t g \int_a^{+\infty} \frac{\left(a^3\delta - (a^3\delta^3/3b^2)\right)^2}{4r^6} r\,dr = \frac{\pi\rho_t g a^2\left(\delta - (\delta^3/3b^2)\right)^2}{16} \tag{5}$$

Because of very light quality of inside liquid column, its gravity potential energy may be ignored in order to simplify calculation.

3.2.2 Surface Potential Energy

When liquid column and crater were formed, new surfaces were created. External surface of the outside liquid column was revolutionary curve shape, which was formed by the curved described by Eq. (4) revolving around h axial. To obtain the created surface S_1, original plane area should be substracted,

$$S_1 = 2\pi \int_0^{a/3} r\left[1 + \left(\frac{dr}{dh}\right)^2\right]^{1/2} dh - 2\pi \int_a^{\infty} r\,dr$$

From Eq. (4), we can obtain

$$dh = \frac{(3a^3\delta/2) - (a^3\delta^3/2b^2)}{r^4} \quad \text{and} \quad \frac{dr}{dh} = \frac{r^4}{(3a^3\delta/2) - (a^3\delta^3/2b^2)}$$

Then, new surface S_1 is

$$S_1 = 2\pi\left[\int_a^{+\infty} \frac{\left(\left((3a^3\delta/2) - (a^3\delta^3/2b^2)\right)^2 + r^8\right)^{1/2}}{r^3} dr - \int_a^{+\infty} r\,dr\right]$$

$$= 2\pi \int_a^{+\infty} \frac{\left(\left((3a^3\delta/2) - (a^3\delta^3/2b^2)\right)^2 + r^8\right)^{1/2}}{r^3} dr$$

Using a Taylor expansion, we can obtain

$$S_1 = 0.1084\pi\sqrt{3a^3\delta - \frac{a^3\delta^3}{b^2}} \tag{6}$$

The surface area of crater in liquid target is

$$S_2 = \int\int\sqrt{1 + \frac{b^2(x^2+y^2)}{a^4 - a^2(x^2+y^2)}}\,dx\,dy$$

New created surface area is obtained by subtracting original plane area from the surface area of crater.

$$S_2 = \frac{\pi a^2 b}{\sqrt{a^2-b^2}}\arcsin\delta\sqrt{\frac{a^2-b^2}{a^4}} + \pi\delta\sqrt{\left(\frac{b^4}{a^4}-\frac{b^2}{a^2}\right)\delta^2 + b^2} - \pi\frac{a^2\delta^2}{b^2} \tag{7}$$

The experiment showed that interface between inside and outside liquid column is column shape. So new created vertical surface area (S_3) is

$$S_3 = \frac{\pi a(3b^2\delta - \delta^3)}{3b^2} \tag{8}$$

Because of the light quality of inside liquid column, gravity potential energy may be ignored, while its surface potential energy is very large. The pressure between inside and outside liquid column caused on the top of inside liquid column is much higher than that of outside liquid column. The pressure between inside and outside liquid column is the function of impacting velocity, liquid target stickness, density and surface tension, which is difficult to be deduced. According to the experimental results, the height of inside liquid column is $0.6a$ (see Table I). Since the entire surface of inside liquid column should be considered, S_4, the surface of the part of inside liquid column higher than outside liquid column, is

$$S_4 \cong 2[1.2\pi a^2] \cong 2.4\pi a^2 \tag{9}$$

TABLE I The results of liquid drops impacting liquid multi-layers target

Falling height, t mm	2 mm *thick liquid layer*				5 mm *thick liquid layer*				8 mm *thick liquid layer*			
	V, mm/s	*D,* mm	*Ho,* mm	*Hi,* mm	*V,* mm/s	*D,* mm	*Ho,* mm	*Hi,* mm	*V,* mm/s	*D,* mm	*Ho,* mm	*Hi,* mm
600	343	21.5	3	7	343	18.7	2.9	7	343	18	2.8	6.8
900	420	22.9	3.4	8.9	420	19.9	3	7.8	420	20.5	3.1	8.2
1200	485	23.4	4.4	9.5	485	21.8	4.5	9.3	485	22.1	3.1	8.5
1500	542	25.2	4.5	10.6	542	23	5.1	11	542	23.2	5	10.8

V – Impacting velocity; *D* – Maximum cavity diameter; *Ho* – Outside splashing wave height; *Hi* – Inside splashing wave height.

From Eqs. (6–9), we can obtain the new created total surface of crater and liquid column

$$\sum S = S_1 + S_2 + S_3 + S_4$$

The total surface potential energy of system (U_3) is

$$U_3 = \gamma \sum S \tag{10}$$

where γ is the surface tension of liquid.

3.2.3 *Other Energy*

Sound energy would also be generated when liquid drops impacted liquid target. According to Franz's formula [6], if impacting velocity is 700 cm/s the total sound energy from impacting process is so small that it can be ignored. Sound energy of low stickness liquid, due to its small diffusion energy, may also been ignored.

3.3 The Formula of Maximal Diameter of Crater

In order to obtain the formula of maximal cavity diameter, the ratio of the energy used to form crater and the total energy must be calculated. When the thickness of liquid layer is infinite, the target should be considered as half infinite target whose energy conversion coefficient is 0.574. By fitting the experimental results in Table I, energy conversion coefficient was $0.574th\,(0.23449\delta^2 + 0.33967\delta)$. When the diameter of the impacting cavity reaches the maximum, all the energy transferred to liquid target will be transformed into potential energy entirely.

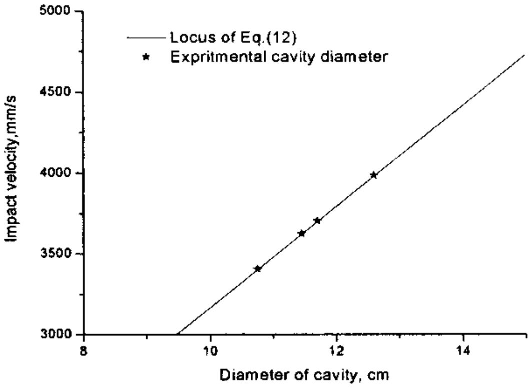
$$U_1 + U_2 + U_3 = 0.048\pi d^3 \rho_d V^2 th(0.23449\delta^2 + 0.33967\delta)$$

where d is the diameter of liquid drop, ρ_d is the density of liquid drop, V is the impacting velocity.

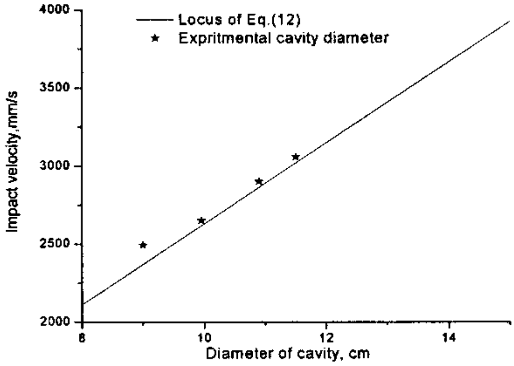
By substituting Eqs. (3), (5) and (10) into the above equation, the following equation was obtained,

$$\begin{aligned} &\pi\rho_t g\left(\frac{9a_m^2\delta^2}{16} - \frac{7a_m^2\delta^4}{24b_m^2} + \frac{a_m^2\delta^6}{144b_m^4}\right) \\ &\quad + \pi\gamma\left(0.1084\sqrt{3a_m^3\delta - \frac{a^3\delta^3}{b_m^2}} + \frac{a_m(3b_m^2\delta - \delta^3)}{3b_m^2} + 2.4a_m^2\right. \\ &\qquad \left. + \frac{\pi b_m^2 a_m}{\sqrt{b_m^2 - a_m^2}}\arcsin\sigma\sqrt{\frac{b_m^2 + a_m^2}{b_m^4}} + \pi\delta\sqrt{\left(\frac{a_m^4}{b_m^4} - \frac{a_m^2}{b_m^2}\right)\delta^2 + a_m^2} - \pi\frac{a_m^2\delta^2}{b_m^2}\right) \\ &= 0.048\pi d^3\rho_d V^2 th(0.23449\delta^2 + 0.33967\delta) \end{aligned} \tag{11}$$

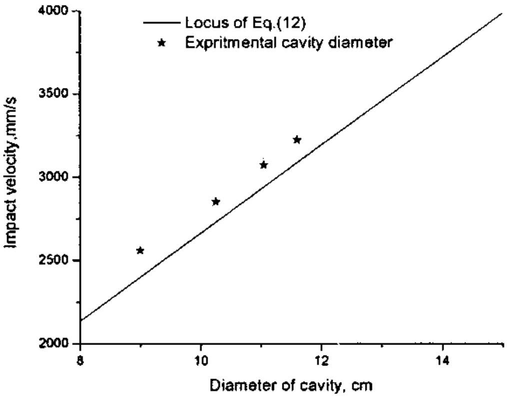
where a_m is short axial radius of ellipsoid crater, b_m long axial radius of ellipsoid crater.



a 2mm liquid layer thickness



b 5mm liquid layer thickness



c 2mm liquid layer thickness

FIGURE 7 The curve of maximal crater diameter of liquid drops impacting multi-layers target against impact velocity.

If the thickness of liquid layer is very small, for example in the protecting screen of spacecraft, its ellipsoid crater can be considered as column shape approximately. In this case, since b_m is infinite, the formula (11) can be expressed in the following way:

$$\pi\rho_t g\frac{9a_m^2\delta^2}{16}+\pi\gamma\left[0.1084\sqrt{3a_m^3\delta}+3a_m\delta+2.4a_m^2\right]$$
$$=0.048\pi d^3\rho_d V^2 th(0.23449\delta^2+0.33967\delta) \quad (12)$$

4. NUMERICAL CALCULATION OF LIQUID DROPS IMPACTING LIQUID MULTI-LAYERS TARGET

In order to verify the accuracy of the equation of maximal cavity diameter, three instances, $\delta = 0.2$, 0.5 and 0.8 mm, where δ is the thickness of liquid target, were calculated and the calculated results were compared with the experimental results. Three numerical calculations were finished under the condition that the mass of liquid drop was equal and liquid targets were seed oil, water and glycerin respectively.

In the standard unit, $g = 980.095$, $\rho_d = 1$, $\rho_t = 0.884$. The surface tension of liquid target γ is 32.736. So Eq. (12) becomes

$$489.778a^2\delta^2+6.14633\sqrt{a^3\delta}+98.208a\delta+78.566a^2$$
$$=0.1508V^2d^3 th(0.23449\delta^2+0.33967\delta)$$

According to the relation between impact energy and maximal crater diameter showed in the Fig. 7a–c, the experimental results were in agreements with the curves.

5. CONCLUSION

The disciplines of the crater forming by liquid drop impacting multi-layer liquid target was presented through the impact experiments and theoretical analysis. The results included that: (1) within a certain impact energy range, the phenomena of impacting crater only occured in the first liquid layer target, (2) interfacial energy was an important parameter which can influence the impacting crater if the liquid layers cannot dissolve each other and (3) the empirical formula was achieved to predict the biggest crater diameter of the impacting crater.

Under the ultra-hypervelocity impact condition, there will be the metal material fluidity phenomena near the contact point of metal protective structure. If the protective structure were constructed by multi-uninterval metal target, which cannot dissolve each other under melting state, the protective effect can be simulated by the impact of liquids at room temperature. The reliability of the simulation results need to be verified by comparison with the hypervelocity impact results. Preliminary investigation indicated that the results achieved from the liquid simulation experiment showed multi-layer metal protection structure can improve the protective effect. The disciplines achieved through the liquid drop simulation study can provide the references for the design of the protective structure of spacecraft.

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