EXPERIMENTAL STUDY ON THE EFFECT OF HEAD CONE ANGLE ON THE LOW VELOCITY OBLIQUE INLET PROCESS OF PROJECTILE

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Abstract: In order to study the influence of the head cone angle and velocity of truncated cone-shaped projectiles on the cavitation and trajectory characteristics under the condition of low-speed oblique entry into water, based on the high-speed camera method, the comparative experiments of different truncated cone-shaped projectiles at low-speed oblique entry into water were carried out, and the effects of the head cone angle and velocity of truncated cone-shaped projectiles on the entry cavitation, movement speed and pitch angle were obtained. The experimental results show that the smaller the cone angle of the truncated cone projectile's head, the earlier the tail collides with the lower wall of the bubble. The smaller the head cone angle is, the faster the initial velocity is, and the later the time of deep closure of the cavitation is. The cavitation of the projectile increases with the decrease of the head cone angle and the increase of the velocity. Velocity and head cone angle have influence on the stability of water inflow. When the velocity of projectile is lower than the critical value, it tends to increase, and when it is higher than the critical value, it tends to decrease.

Key words: truncated cone; ballistic characteristics; head cone angle; inflow stability; critical value

Introduction

The low-speed water entry process of projectile is a complex two-phase coupling process, and the impact of water entry will produce a series of transient physical problems. In the process of entering water across the free liquid surface, air will be drawn into the water to form voids, and the formation, expansion,

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closure and collapse of voids will affect the movement and hydrodynamic characteristics of the entry navigation. Among them, the structure and shape of the projectile head have an important impact on the void and ballistic characteristics.

In recent years, many scholars at home and abroad have studied the low-speed water-entry cavitation of projectiles from different perspectives.Yan et al[1]recorded the evolution of void morphology during free fall of a sphere into water at low Froude number with a high-speed camera, and presented an asymptotic theory describing the law of void development.Bergmann et al[2] studied the development of voids in a disc with Froude number less than 200 by experimental and numerical methods. Aristoff et al[3-4] carried out experimental and numerical studies on the vertical inflow of light spheres. The dynamic process of the sphere and the effect of the velocity attenuation of the sphere on the void morphology were described.Wei et al[5] recorded the evolution process of the void morphology of the sphere entering water with a high-speed camera, calculated the change of the velocity of the sphere entering water, and gave the formula for predicting the velocity of the sphere entering water. He Chuntao et al[6-7] carried out a study on the cavitation morphology of a cylindrical body entering water at low speed, studied the evolution process of the cavitation entering water under the condition of multi-projectiles in tandem and parallel, and analyzed the interaction between the cavitations and the influence of multi-projectiles on the cavitation under the condition of tandem.Truscott et al. [8] comprehensively summarized a large number of experiments, theories and numerical analysis on water inflow by foreign scholars. Yang Heng et al[9] carried out low-speed water inflow experiments on round-nosed projectiles, 90 degree cone-nosed projectiles, 120 degree cone-nosed projectiles and 150 degree cone-nosed projectiles. Ma Qingpeng et al[10] carried out an experimental study on the flow characteristics of a sphere vertically entering a water void, and analyzed the influence of surface wetting on the entry void.Wei [11] carried out an experimental study on the horizontal inflow cavitation of a cylinder. Duan Yu et al[12] carried out an experimental study on the flow characteristics of a cylindrical shell with flat head, conical head and spherical head into water. Scolan et al[13-14] studied the oblique penetration of three-dimensional projectiles into water, and analyzed the variation of surface physical quantities of wet projectiles. Jiang Yunhua et al[15] carried out an experimental study on the flow characteristics of incoming cavitations with and without constraints of moving bodies. Zhou Jie et al[16] used SPH method to simulate the process of projectile entering water, and analyzed the influence of projectile shape, velocity and angle of entering water on the flow characteristics of cavitation.

Based on the existing literature, the influence of truncated cone head shape on oblique water void and ballistic parameters has not been reported.Based on this, this paper studies the influence of the size of the truncated cone nose projectile's head diameter on the inflow cavitation and ballistic characteristics under the condition of low-speed inclined water entry, compares and analyses the two different working conditions, and obtains the law of the influence of the size of the truncated cone nose projectile's head diameter on the inflow cavitation, pitch angle and velocity, which provides a certain reference for the design of the water entry projectile.

1 Experimental System and Model Parameters

The sketch diagram of the inclined water entry experimental device is shown in Fig. 1, which mainly includes glass tank, high-speed camera, computer, light source, guide rail, support, coordinate paper, bottom protective layer of the tank, etc.The tank is made of 15 mm thick ordinary glass, with a protective layer at the bottom, covering the bottom of the tank. In the experiment, guideway was used to guide the projectile to fall, 1300W advertising light source was used to illuminate the projectile, Phantom high-speed camera was used to photograph the evolution process of the incoming cavitation at 4100 frames/s, and tap water was used for the experiment.

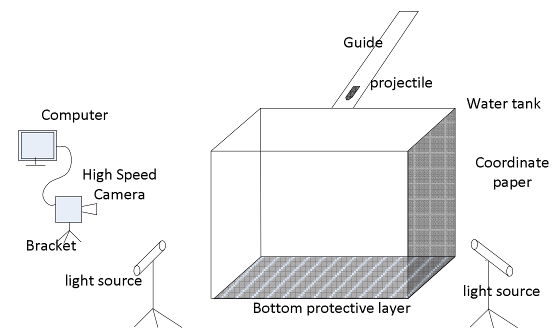


Figure 1. An experimental device for oblique water entry e.

As shown in Fig. 2, the projectile model consists of two parts: a truncated cone at the head and a cylinder at the tail.The length L of all models is 35 mm, and the diameter D is 7 mm.The diameter of the truncated cone head is 4 mm, and the angle between the truncated cone head and the projectile cylinder (represented by the truncated cone head cone angle below) is 30 degrees, 45 degrees and 60 degrees, respectively. In this paper, model A, model B and model C are used to represent the truncated cone head. The projectile material is 45 steel.

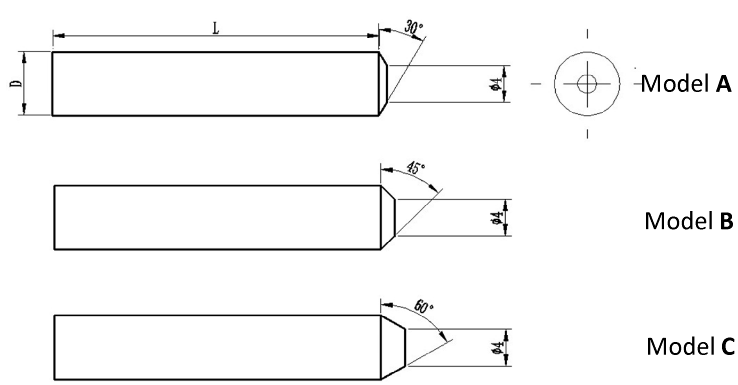
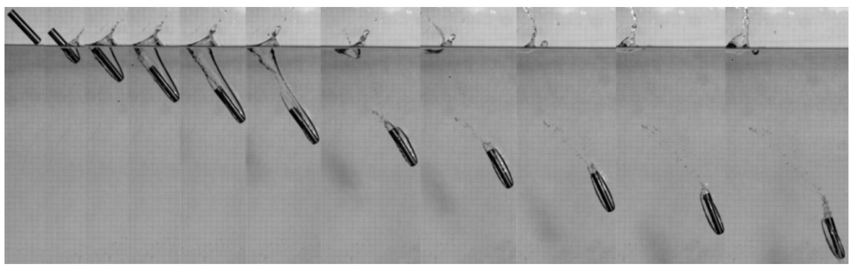


Figure 2. Projectile model.

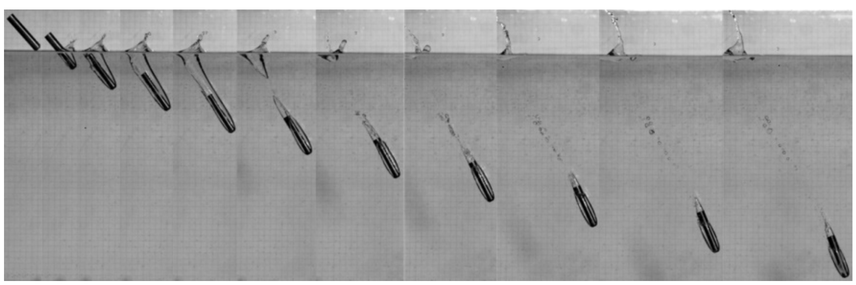
2. Experimental results and analysis

2.1 Effect of Cone Angle and Initial Velocity of Projectile Head on Inlet Cavitation

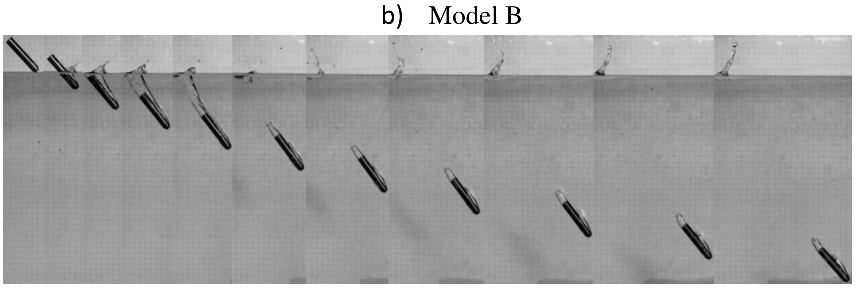
Using the experimental system established in Fig. 2, the oblique penetration experiments of projectiles were carried out to study the effects of the cone angle of the truncated cone-shaped projectile head on the shape, motion and hydrodynamic characteristics of the water-entry cavitation.The time when the head of the projectile touches the water surface is taken as t=0, and the water entry angle is 45 degrees. Fig. 3, 4 and 5 are the navigation attitude and water inflow evolution charts of each model with initial velocity of 1.95 m/s from water inflow to 100 ms, 2.63 m/s from water inflow to 80 ms, and 3.35 m/s from water inflow to 70 ms, respectively. The time difference between adjacent projectiles in each chart is 10 ms.



a) Model A



b) Model B

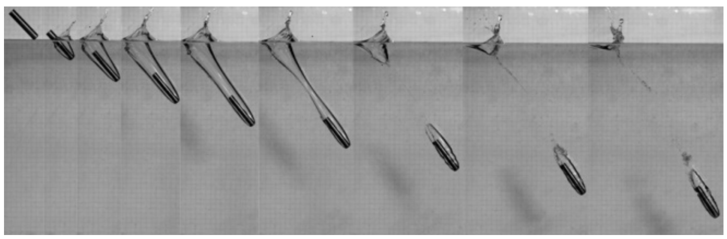


c) Model C

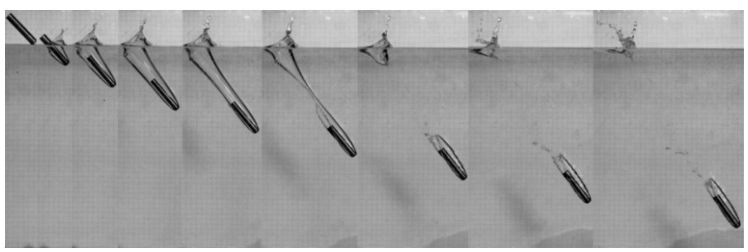
Figure 3. Inlet navigation attitude and bubble evolution chart with initial velocity of 1.95m/s.

Fig. 3 shows the attitude and bubble evolution of each model at the initial speed of 1.95m/s. Deep closure occurred in all models. The voids on the near side of model A and B are smaller than those on the far side of model A. Model B is smaller than that on the near side of model A, while model C has no voids near the water surface after entering the water. This is because the projectile velocity is small, the pressure is small when it collides with the water surface, and the cone angle of model C is large, the transition of water flow from the truncated cone head to the cylinder part is smooth, so there is no cavitation near the water surface. The tail of model A and B collides with the bottom wall of the cavity before deep closure, and model A collides earlier; model C closes first, model B next and model A the latest; after the closure of the cavity, the tail of the projectile moves towards the upper wall of the cavity. Observing the attitude of the projectile and the tail jet, it is easy to know that the pitch angle of model A increases fastest.

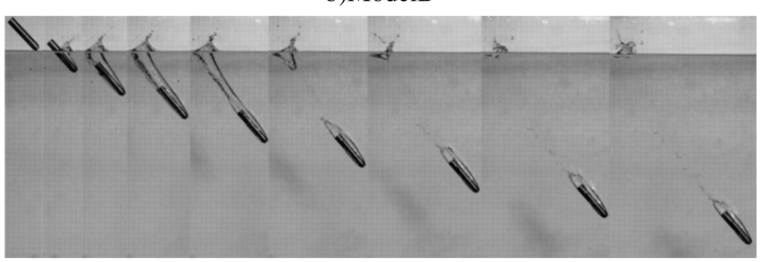
By measuring the size of the incoming cavitation, it can be seen that model A is the largest, model B is the second, and model C is the smallest. After deep closure, the void around model A is the largest, then model B is the smallest, and only part of the projectile is wrapped around model C. The law of the void around the liquid surface is the same.



a)Model A



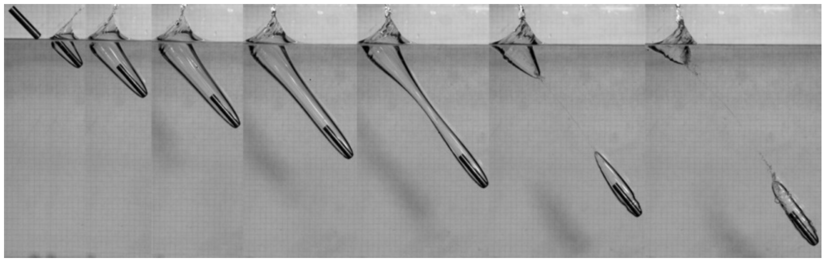
b)ModelB



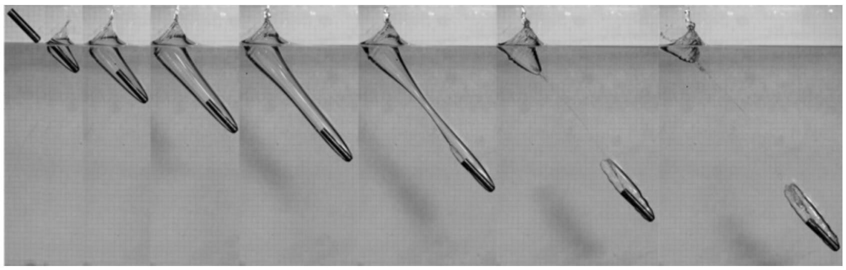
d) Model C

Figure 4. Inlet navigation attitude and bubble evolution chart at initial velocity of 2.63m/s.

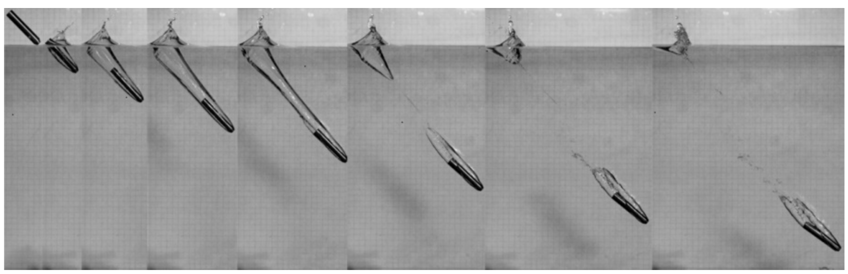
Fig. 4 shows the navigation attitude and bubble evolution charts of each model at 2.63m/s initial velocity, which is similar to that of 1.95m/s initial velocity. The void sizes of each model were measured. Compared with the initial velocity of 1.95m/s, the void size of 2.63m/s model was larger.



a) Model A



b) Model B



c) Model C

Figure 5. Inlet Navigation Attitude and Bubble Evolution Chart at Initial Velocity 3.35m/s.

Fig. 5 shows the navigation attitude and bubble evolution diagram of each model at 3.35m/s initial velocity, which is similar to that of 1.95m/s initial velocity. The void sizes of each model were measured. Compared with the initial velocity of 2.63m/s, the void size of the same model was larger than that of 3.35m/s.

In conclusion, comparing the different models' attitude and void evolution at the same speed, model A has the largest void, model B takes the second place and model C the least; model C has the earliest void depth closure, model B takes the second place and model A the latest. When the velocity is 1.95m/s and 2.63m/s, the model C is close to the liquid surface and does not produce cavitation. That is to say, the smaller the cone angle of the head projectile, the larger the vacuole and the later the deep closure. Comparing the different velocity attitude and void evolution of the same model, it can be seen that the lower the velocity, the earlier the projectile tail touches the lower wall of the void; the higher the velocity, the larger the void. The analysis shows that when the projectile velocity is low, the projectile is heavily influenced by gravity and falls as a whole, and the projectile tail touches the lower wall of the cavity earlier; when the projectile velocity is high, the energy transmitted to the basin is more, the flow separation is faster, and the cavity is larger.

Table 1. Deep closure moment of Water entry cavity.

Projectile model	Deep closure time/(ms)		
	Initial velocity1.95m/s	Initial velocity2.63m/s	Initial velocity3.35m/s
Model A	51.71	53.66	54.63
Model B	49.27	50.98	52.92
Model C	44.39	45.61	47.80

The void closure time of the above experiments is recorded as shown in Table 1. Comparing the different models of the deep closure time at the same initial velocity, it can be seen that the change rule of the deep closure time is the same under three different initial velocities. In other words, model A has the longest deep closure time, model B takes the second place and model C the shortest. The analysis shows that the cone angles of model A, B and C increase in turn, and the void size decreases in turn. After the same velocity enters the water, the deep closure time becomes earlier, that is to say, the smaller the cone angle, the later the deep closure time.

Comparing the closure time of the same model at three different initial velocities, we can also find that the higher the initial velocity, the later the closure time. The analysis shows that the higher the initial velocity of the same model, the larger the void, and the later the closure time of the void.

2.2 Effect of Cone Angle and Initial Velocity of Projectile Head on Pitch Angle

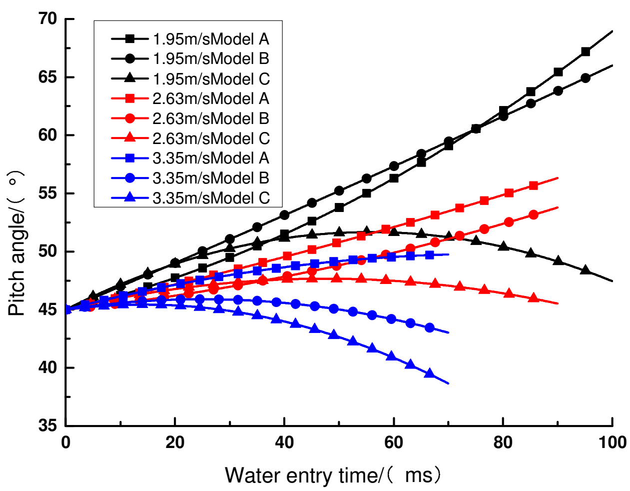


Figure 6. Variation of pitch angle.

Fig. 6 shows the pitch angle of each model after entering water at different initial velocities. Comparing the pitch angle curves of each model at the same velocity, it can be seen that the pitch angle of model A is the largest, model B is the second, model C is the smallest, and the pitch angle decreases with the increase of the cone angle. The elevation angle of model A shows a non-linear change law of increase, model C shows a non-linear change law of increase first and then decrease, while model B shows an increasing trend of elevation angle when it enters water with 1.95m/s and 2.63m/s, and a non-linear change law of increase first and then decrease when it enters water with 3.35m/s. The change of pitch angle is due to the influence of resultant moment of projectile after entering water.

Comparing the pitch angle changes of different velocities of the same model, it can be seen that the pitch angle changes in a larger range when the projectile velocity is low. The faster the initial velocities of model A, B and C, the smaller the pitch angle.

The reason is that when the initial velocity is small, the impact of projectile moment is greater in the same time, and when the initial velocity is large, the impact of projectile moment is smaller, and when the initial velocity is large, the moment produced by the vertical resultant force is relatively larger, which makes the pitch angle decrease gradually. In conclusion, both the velocity and the cone angle of the head have some effects on the stability of water inflow.

2.3 Effect of Cone Angle and Initial Velocity of Projectile Head on Velocity Change

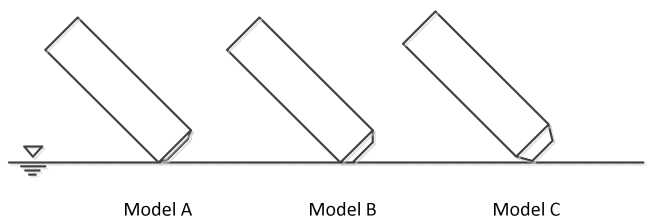
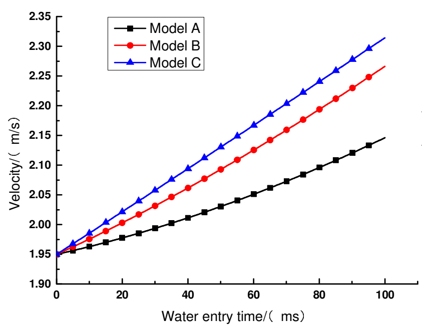
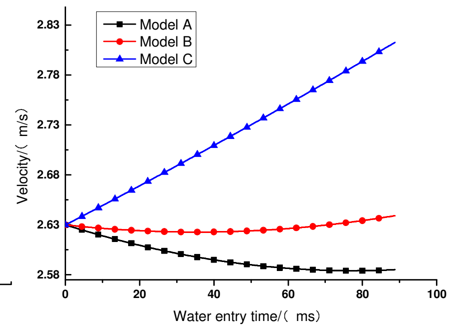


Figure 7. Water-entry collision diagram at t=0.

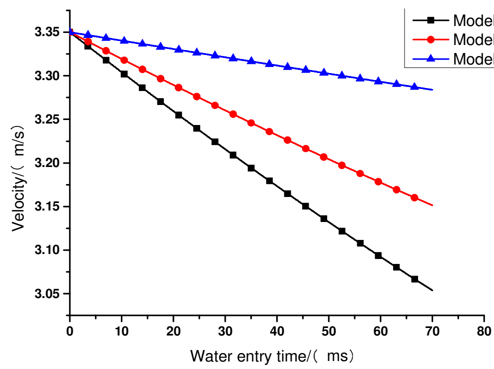
Figure 7 shows that the contact points with water surface are different when the models enter water. The contact point between the cylinder part of model A and the truncated cone part is the contact point, while the surface of the truncated cone part of model B contacts with the water surface on one side, and the head point of the truncated cone of model C is the contact point. Pixel acquisition points are selected as the first point where the warhead contacts the water surface, and the displacement curve is obtained by the experimental water entry chart. Then the time-varying curves of the warhead velocity are obtained by derivation calculation of the curve.



a) Inlet velocity 1.95m/s



b) Inlet velocity 2.63m/s



c) Inlet velocity 3.35m/s

Figure 8. Velocity changes with time.

From Figure 8, it can be seen that when the initial velocity is different, the trend of velocity change of each model is different after entering water. When the initial velocity is 1.95m/s, the speed of each model increases, the speed of model C increases fastest, model B takes second place and model A is the smallest. When the initial velocity is 2.63m/s, the velocity of model C increases, while the velocity of model B and C decreases. When the initial velocity is 3.35m/s, the velocity of each model decreases. Model A attenuates the fastest, model B takes the second place and model C the slowest. Analyzing the process of projectile entering water, it can be seen that the horizontal resistance of projectile to the left leads to the decrease of horizontal velocity, and the vertical resultant force to the downward leads to the increase of vertical velocity. When the initial velocity of projectile is low, the resultant velocity increases after entering water, and when the initial velocity increases over the critical velocity, the resultant velocity decreases. When the cone angle of the projectile head is large, the flow from the projectile head is smooth, the energy loss is small, and the water resistance is the smallest. Therefore, the velocity of model A increases the fastest and the critical velocity is the highest.

In conclusion, when the initial velocity is greater than the critical velocity, the bigger the cone angle of the truncated cone-shaped projectile is, the bigger the water entry resistance is, and the faster the velocity attenuation is; when the initial velocity is less than the critical velocity, the bigger the cone angle of the projectile is, the smaller the velocity increase is.

The Weber number *We* are:

$$We = \rho v^2 l / \sigma \qquad (1)$$

In the formula: V represents the initial water inflow velocity of projectile, l represents the characteristic length of projectile, and the surface flow usually takes the flow length as the characteristic length. Therefore, the sum of the head diameter and the length of two buses of the truncated cone is the characteristic length l, and the surface tension coefficient of the fluid σ is 0.075N/m.

Table 2. Weber number*We.*

Initial velocity/（m/s）	*We*		
	Model A	Model B	Model C
1.95	0.38	0.42	0.51
2.63	0.69	0.76	0.92
3.35	1.12	1.233	1.50

The calculated Weber number is shown in Table 2. According to our formula, the greater the velocity is, the greater the influence of inertia force is, and the smaller the influence of surface tension is. So we only need to discuss Weber number of different models under the same working condition.When the initial velocity is different, the Wes of model A, B and C increase in turn, and the influence of surface tension decreases in turn. Because surface tension reflects the resistance of projectile, the velocity of model A decreases fastest at lower velocity, the velocity of model C decreases slowest, and model B is in the middle.When the speed is higher, the speed of model A increases the slowest, model C increases the fastest, and model B is in the middle, which is consistent with the velocity curve of figure 8 in this paper.

The calculation formula of Froude number *Fr* is as follows:

$$Fr = v / \sqrt{l * g} \qquad (2)$$

In formula V, the initial velocity of the projectile entering water, l, the characteristic length of the projectile, and g, the acceleration of gravity.

Table 3. *Fr*.

Initial velocity/（m/s）	*Fr*		
	Model A	Model B	Model C
1.95	7.22	6.86	6.23
2.63	9.74	9.25	8.40
3.35	12.41	11.79	10.70

The calculated *Fr* is shown in Table 3. Hourly gravity plays a dominant role and inertial force plays a dominant role when *Fr* is large. It can be seen that the inertia force plays a dominant role and the speed decreases in case 1, while gravity plays a dominant role in case 2, and the speed increases. At the same initial velocity, the *Fr* of model A is the largest and that of model C is the smallest.Therefore, in the case of initial velocity 1.95m/s and 2.63m/s, the speed of model A increases the slowest, the speed of model C increases the fastest, and model B is in the middle; in the case of initial velocity 3.35m/s, the speed of model A decays the fastest, the speed of model C decays the slowest, and model B is in the middle, which is consistent with the curve of velocity variation in Figure 8 in this paper.When *Fr* is at a critical value, the inertia force and gravity have the same effect on the velocity. The effect of inertia force and gravity on the velocity cancels each other. The velocity is the critical velocity, which is shown in the fact that the acceleration of vertical velocity increase and the acceleration of horizontal velocity attenuation just cancel the effect on the velocity.

3 Conclusion

Based on the high-speed photography system, this paper studies the influence of the size of the head cone angle and the initial velocity of the truncated cone projectile on the cavitation and ballistic characteristics under the condition of low-speed oblique water entry, compares and analyses the phenomenon of low-speed oblique water entry of different models, and obtains the law of the influence of the head cone angle on the water entry cavitation, velocity and pitch angle of the truncated cone projectile. The concrete conclusions are as follows:

1） The smaller the cone angle of the truncated cone head, the earlier the tail collides with the wall below the bubble; the smaller the cone angle of the head, the faster the initial velocity, and the later the closing time of the cavity depth; the bubble of the truncated cone head increases with the decrease of the cone angle of the head and with the increase of the velocity.

2）The velocity and the cone angle of the head have influence on the stability of water entry, and the pitch angle of the projectile varies greatly when the velocity of the projectile is low.

3）When the water entry velocity of the truncated cone-nosed projectile is lower than its critical value, the water entry velocity of the projectile shows an upward trend and a downward trend when the water entry velocity of the truncated cone-nosed projectile is higher than the critical value. The critical velocity shows that the acceleration of vertical velocity increase and that of horizontal velocity attenuation just offset the effect of combined velocity. When the projectile enters the water at the critical velocity, the combined velocity remains basically unchanged in a certain range.