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Special Features of High-speed Interaction of Supercavitating Solids in Water

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Abstract. Special features of material behavior of a supercavitating projectile are investigated at various initial velocities of entering water on the basis of the developed stress-strain state model with possibility of destruction of solids when moving in water and interacting with various underwater barriers with the use of consistent methodological approach of mechanics of continuous media. The calculation-experimental method was used to study the modes of motion of supercavitating projectiles at sub- and supersonic velocities in water medium after acceleration in the barrelled accelerator, as well as their interaction with barriers. Issues of stabilization of the supercavitating projectile on the initial flight path in water were studied. Microphotographs of state of solids made of various materials, before and after interaction with water, at subsonic and supersonic velocities were presented. Supersonic velocity of the supercavitating projectile motion in water of 1590 m/s was recorded.

INTRODUCTION

The research on high-speed interaction of solids in water aims at solving a number of interrelated tasks: imposing high initial velocity, overcoming water resistance, providing steady motion and effective interaction with underwater barriers. This last imposes high requirements to the materials used for producing projectiles.

There are plenty of data in scientific literature on each problem of this complex so far. One way of providing necessary motion speed of supercavitating projectile in water is the use of barreled accelerators. To decrease resistance of a solid when it moves in water the supercavitation phenomenon is used, i.e. formation of the gas filled cavity encompassing an underwater projectile in water [1, 2]. The research technique of high-speed interaction of the projectile made of hard-alloy materials with water [3] makes it possible to determine the moment and nature of its destruction.

In the present work, behavior of the material of a supercavitating projectile is analyzed at various speeds of water entry: from insignificant plastic deformations to destruction. Experimental studies were done on the hydroballistic test bench equipped with modern measurement and recording devices. The used ballistic setup provides acceleration of the studied inertial supercavitating projectiles in the wide range of initial speeds – from subsonic to supersonic relative to water medium. To study stress-strain state and possible destruction of solids when moving in water and interacting with various underwater barriers, mathematical models on the basis of consistent methodological approach of mechanics of continuous media are used [4].

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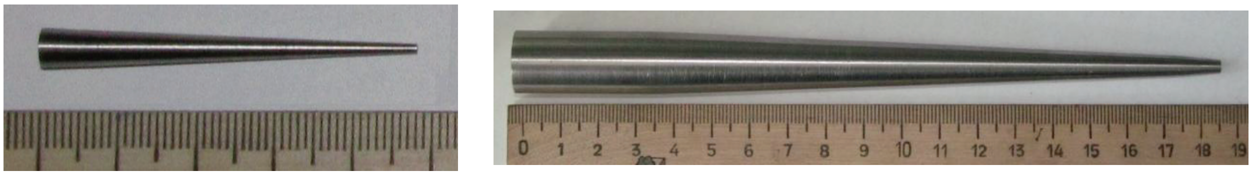
CALCULATION-EXPERIMENTAL RESEARCH

A typical supercavitating projectile is a conic body with a flat end face on top – cavitator. The main modifications studied in the work are presented in Fig. 1.



(a) (b)

FIGURE 1. External view of supercavitating projectile

Due to the features of body shape of the projectile, to save it when moving in the barrel, the guiding device is used. One of the important conditions of steady motion of the supercavitating projectile in water is the separation of the guiding device in an air part of the trajectory [1], saving the rectilinear motion of the projectile when entering water [2,5,6]. Figure 2 presents a still image showing the separation of the guiding device from the supercavitating projectile in an air part of the trajectory. The mass of the projectile presented in Fig. 1 (*b*) was 163 g, at the muzzle speed of 597 m/s. Entering water at a small angle the projectile becomes stabilized in water due to gliding on the cavity surface. High pressures on the surface of contact of the cavitator and water do not allow it to descend from the trajectory. For some time, the projectile glides in the cavity, and then it is stabilized. Figure 3 shows still images of projectile motion in initial (*a*) and late stages (*b*) of gliding. Gliding was observed when the projectile was passing in water the path from 3.4 to 8.0 m. At the beginning of gliding, the diameter of the cavity at a distance of 5 cm from the cavitator is 18.5 mm, in tail part of the projectile – 32.9 mm, the speed of motion is 558.5 m/s. At the end of gliding, the diameter of the cavity at a distance of 5 cm from the cavitator is 18.7 mm, in tail part of the projectile – 31.2 mm, the projectile speed – 502.9 m/s. After covering 4.6 m the projectile reaches the mode of steady motion. The time of motion on this path made 9.4 ms. After covering the distance L = 9.3 m in water, the barrier was hit at a speed of $V \sim$ 490 m/s with deviation of the supercavitating projectile from aiming mark Δ = 0.5 cm or Δ/L = 0.0005. The photograph of the result of interaction of the projectile with the barrier is given in Fig. 4.

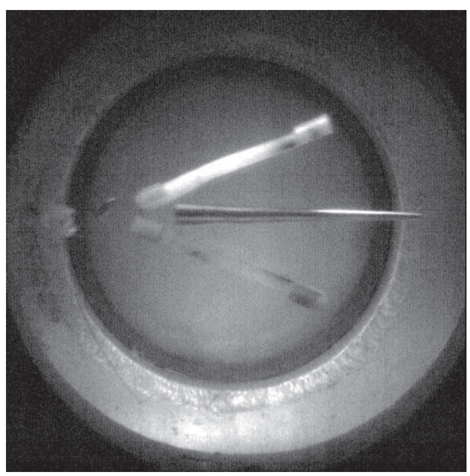
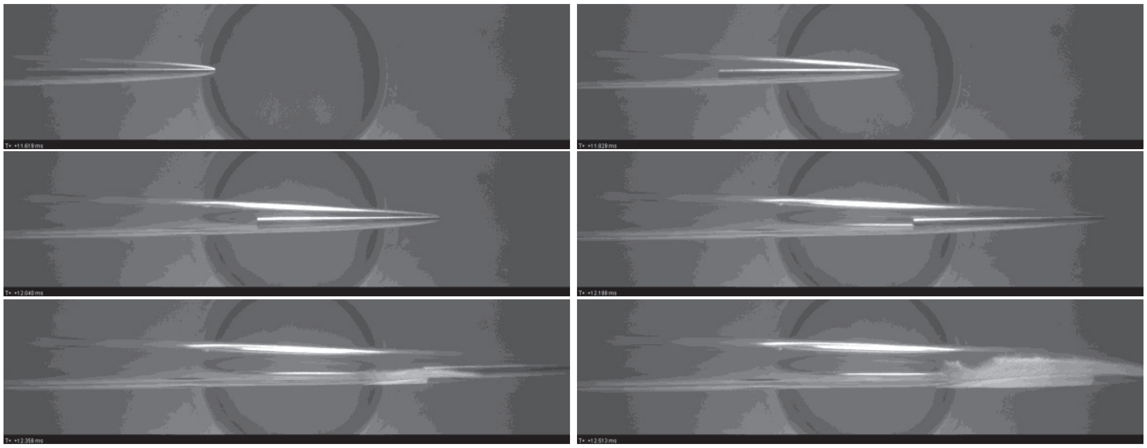
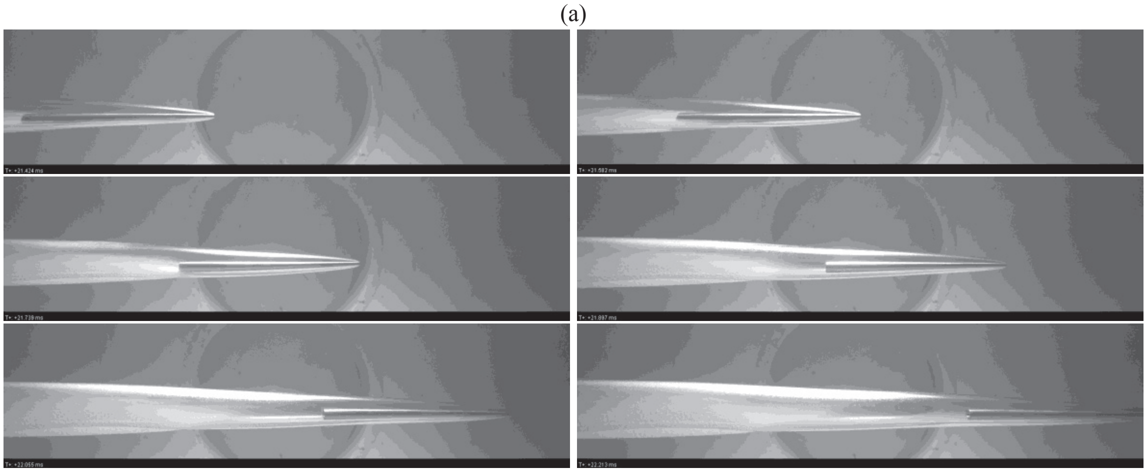


FIGURE 2. Separation of the guiding device from the projectile



(a)



(b)

FIGURE 3. Motion of the supercavitating projectile at gliding stage

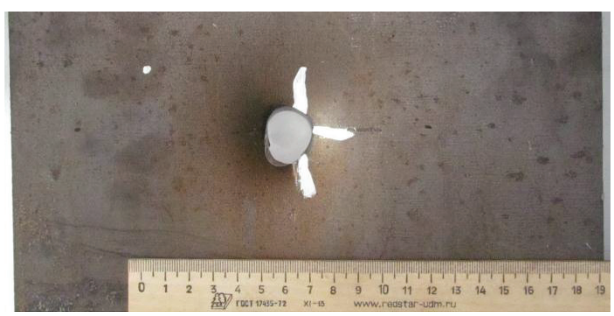
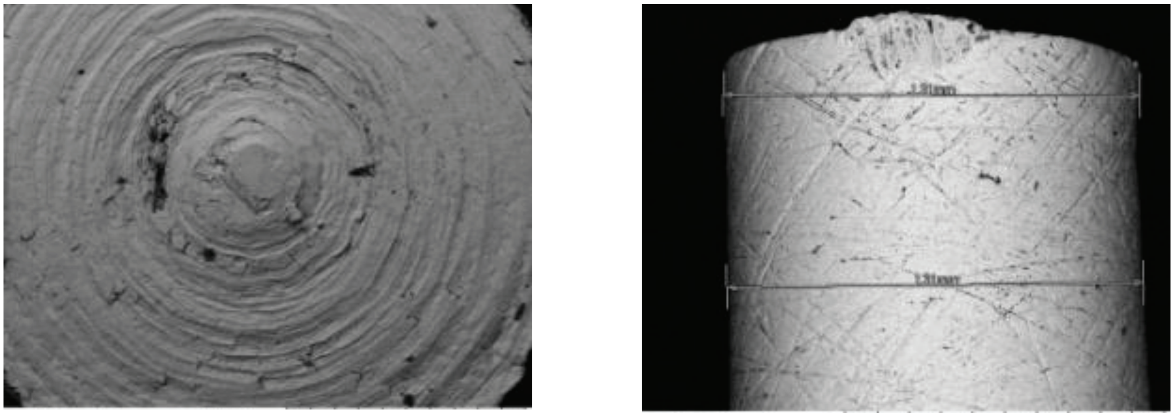


FIGURE 4. The barrier after interaction with the projectile

The high pressure region, which moves together with the projectile, may lead to plastic deformation of the cavitator and even its destruction. The resistance characteristic of the projectile is the limit speed under which it keeps its integrity.

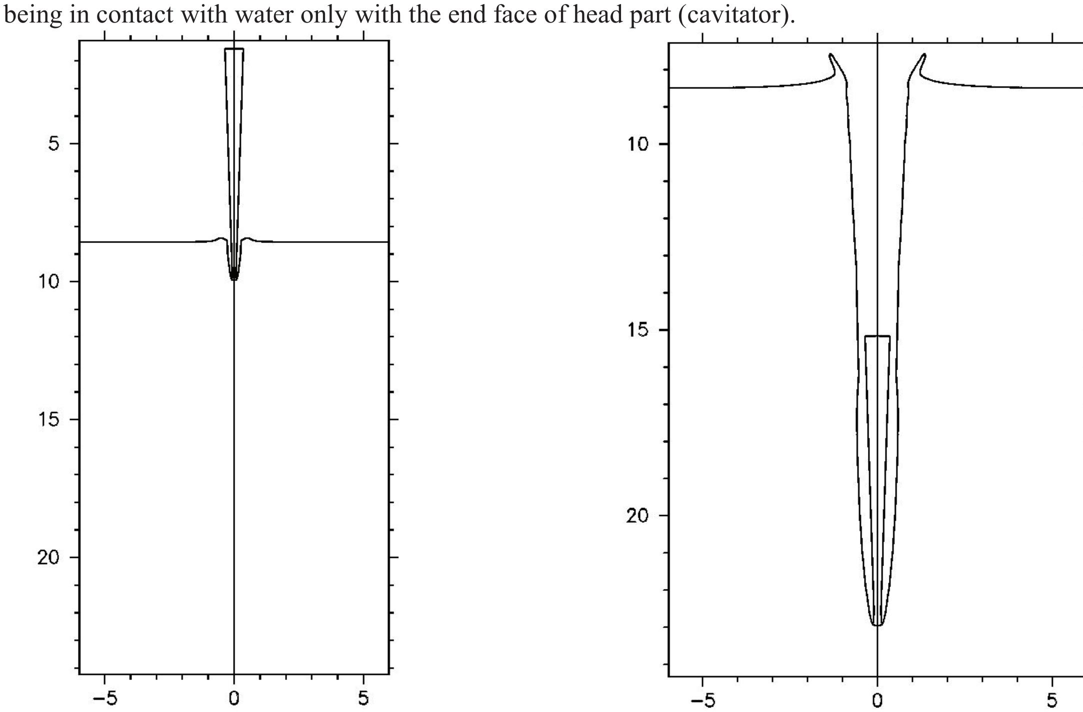
Figure 5 shows the cavitator of steel projectile, which was presented in Fig. 1 (a), after entering water at a speed V_0 = 1090 m/s. The microphotographs prove that the steel cavitator underwent insignificant plastic deformations (the relation of initial diameter to final $d_0/d_к$ = 0.99).



(a) (b)

FIGURE 5. Microphotograph of the steel cavitator after penetrating into water at V_0 = 1090 m/s

Figure 6 presents the results of the performed calculation of an axisymmetric water entry of the projectile confirming the conclusion about insignificant deformability of the projectile in case of steady motion at this velocity. Hereinafter the maximum P_{max} values of pressure, and also values of centre-of-mass velocity of the projectile V_{cm} in the flow field are given in the symmetry plane of cylindrical system of coordinates: z (cm), r (cm). At the initial stage of penetration of the projectile there occurs formation of a supercavity, and then it is inside of a bubble, being in contact with water only with the end face of head part (cavitator).

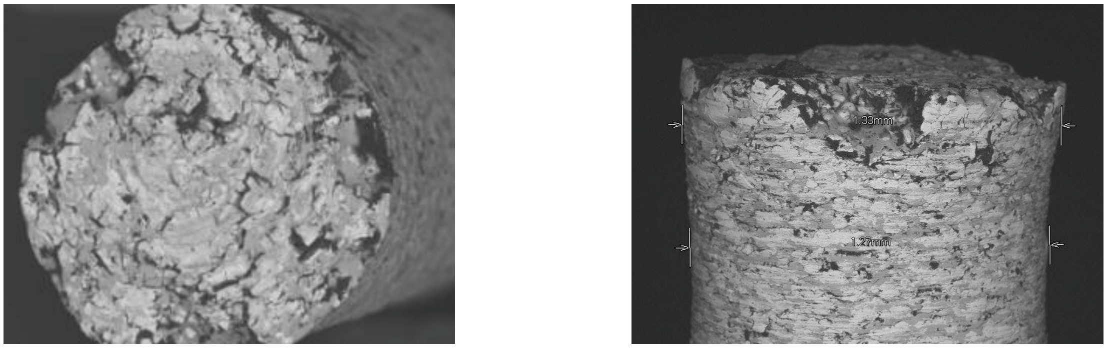


t = 15 μs, P_{max} = 2.1 GPa, V_{cm} = 1070 m/s t = 153 μs, P_{max} = 0.06 GPa, V_{cm} = 960 m/s

FIGURE 6. Chronogram of penetration of the steel projectile into water at V_0 =1090 m/s

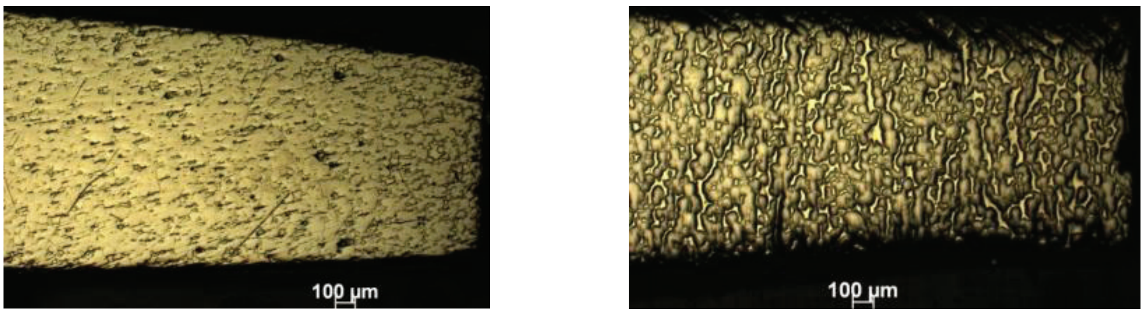
Figure 7 shows the cavitator of the projectile made of hard-alloy TNI-90 material (tungsten, nickel and iron alloy) after entering water at a speed V_0 = 1553 m/s (*a* – end face, *b* – profile).

In this case, at $d_0/d_к$ = 0.95 fragile destruction of a hard-alloy cavitator is observed. The microphotograph of metallographic sections of the cavitator head part made of TNI-90 before (*a*) and after penetrating into water (*b*) (Fig. 8) shows the existence of structural changes in the alloy (large conglomerates – tungsten, light layers – nickel and iron).



(a) (b)

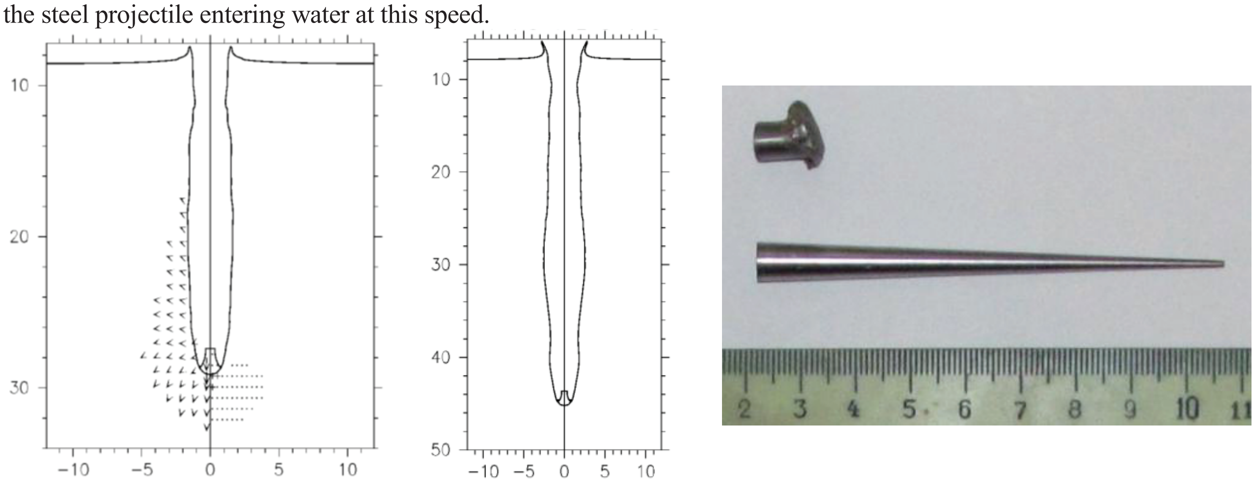
FIGURE 7. Microphotograph of the TNI-90 cavitator after penetrating into water at V_0 = 1553 m/s



(a) (b)

FIGURE 8. Microphotograph of metallographic sections of the TNI-90 cavitator before and after penetrating into water at V_0 = 1553 m/s

Figure 9 illustrates the chronogram of penetration of the steel projectile into water at an initial speed V_0 = 2200 m/s. Fast braking and reducing of the projectile from water are observed. Figure 10 shows deformation and destruction of the steel projectile entering water at this speed.



t = 132 µs, P_{max} = 1.7 GPa, V_{cm} = 1.44 km/s (a)

t = 360 µs, P_{max} = 0.4 GPa, V_{cm} = 0 km/s (b)

(c)

FIGURE 9. Chronogram of penetration of the steel projectile into water and its external view before and after at V_0 =2200 m/s

Figure 10 illustrates the photographic record of motion of the TNI-90 projectile 1 (*a*) accelerated to the velocity V_0 = 1602 m/s. It steadily moves in the supercavity. At a distance of 200 mm from water entry, the velocity V_{cm} = 1590 m/s was recorded. In the cavitator zone in water, an attached shock wave is observed. At a distance of 1267 mm, the projectile penetrates into the 103-mm-thick duralumin barrier by the depth of 62 mm.

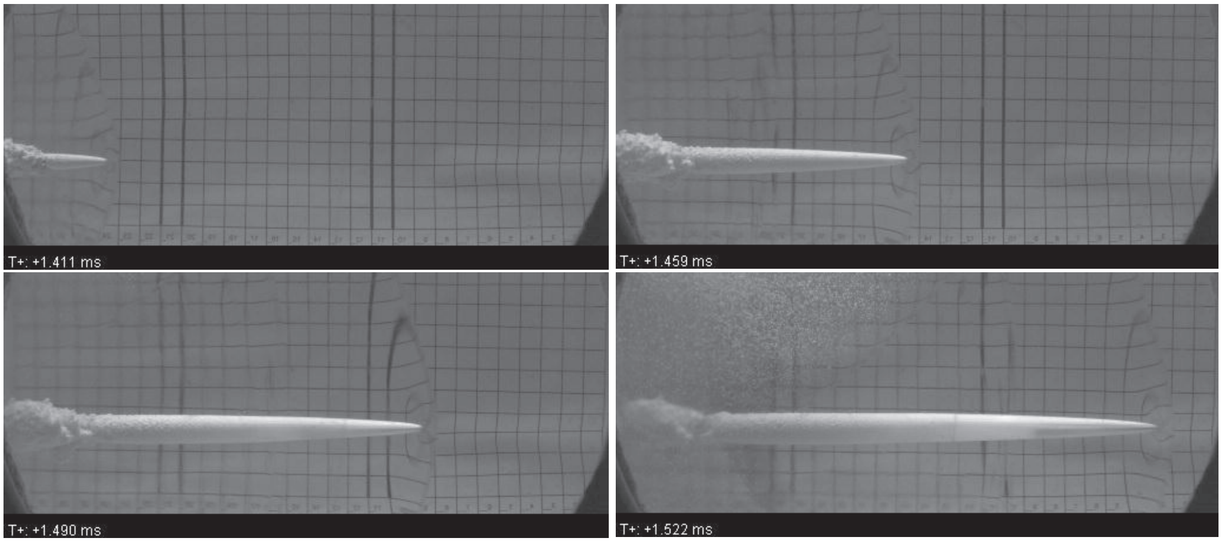
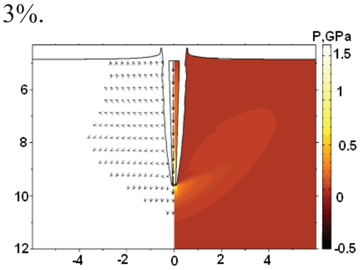


FIGURE 10. Photographic record of motion of the supercavitating projectile in water at the velocity 1590 m/s

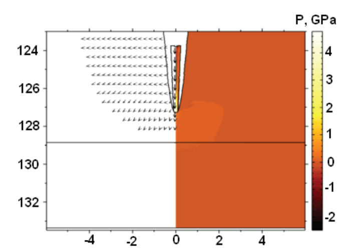
Figure 11 illustrates the results of mathematical modeling in the form of the chronogram of the projectile motion (*a* – water entry, *b* – approach to the barrier, *c* – hitting the barrier). At 3 µs, an attached shock wave is also observed. At 840 µs, the shock wave is reflected from the underwater barrier.

Dependences of resistance force F_x and speed V_{cm} on time are presented in Fig. 12. They reflect the dynamics of projectile motion and penetration into the barrier. When moving in water, the resistance force is almost constant, and the velocity of the projectile drops linearly. Upon reaching the barrier, the resistance force sharply rises, the projectile slows down and stops at 900 µs. The difference with experimental data on crater depth in the barrier does not exceed 3%.



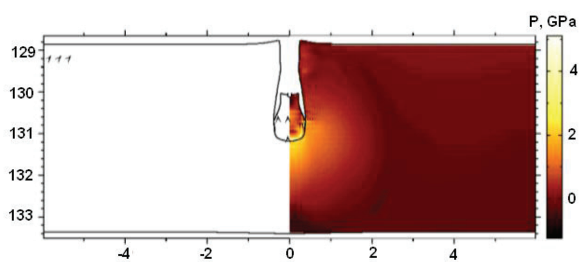
t = 3 µs, V_{cm} = 1610 m/s

(a)



t = 840 µs, V_{cm} = 1305 m/s

(b)



t = 906 µs, V_{cm} = -14 m/s

(c)

FIGURE 11. Chronogram of motion of the supercavitating projectile at V_0 = 1627 m/s

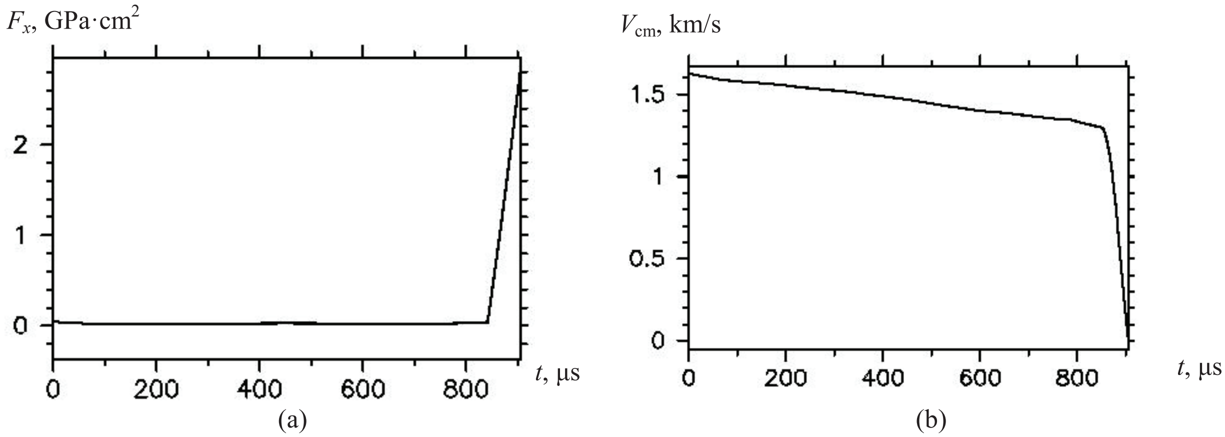


FIGURE 12. Resistance force and speed drop of the solid depending on time at V_0 = 1627 m/s

CONCLUSION

To research processes occurring at the high-speed water entry of the supercavitating projectile and its subsequent interaction with the underwater barrier, the calculation-experimental analysis making it possible to consider hydrodynamic and strength aspects in the wide range of velocities was carried out.

Issues of stabilization of the supercavitating projectile on the initial flight path in water were studied. It was shown that, by gliding in the cavity, the supercavitating projectile gains stability which remains at the subsequent stage of motion.

Strength aspects of interaction of supercavitating projectiles with water medium were considered. Various modes were shown: from nondeformable state to destruction of the cavitator when increasing the velocity of the projectile.

Supersonic velocity of the supercavitating projectile motion in water of 1590 m/s was recorded.

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