EXPERIMENTAL AND THEORETICAL STUDY OF SUPERCAVITATION PHENOMENA ON DIFFERENT PROJECTILES SHAPES

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ABSTRACT

Body shape of high-speed underwater vehicles has a great effect on the Supercavitation behaviour. The transit flow around either partially cavitating or supercavitating body affects the trajectory of high-speed underwater vehicles. Commercial code (ESI-CFD ACE+, V 2010) is used to simulate the supercavitation phenomenon. Cavity shape was determined over projectile body and around wake by high speed camera. This paper compares between the numerical simulation results for the flow of supercavitating on these different nose shapes. Navier-Stokes equations were used as governing equations for simulating supercavitation. Grid designs are structured and unstructured grid. Also, two-dimensional flow field around the cavitating body was determined. Projectile body has a diameter about 0.4 times its length (0.4L).

Key words: supercavitation, experimental, structured grid, unstructured grid, ESI-CFD, hydrofoil, projectile, shape optimization.

INTRODUCTION

High-speed underwater vehicles have many advantages and disadvantages. So, many researchers simulate is behaviour and try to control is trajectory. Mostafa et al. (2001) study experimentally the flow around a hemisphere cylinder by shooting a projectile and employing Particle Image Velocimetry (PIV) to measure the velocity field. A doublet is generated between the projectile nose and its rear end. At high speeds, a vortex ring is situated over the bubble boundary. The flow around either partially cavitating or supercavitating hydrofoils are treated by Kinnas et al. (1994) with a viscous/ inviscid interactive method. Owis and Nayfeh (2003) compute the compressible Multiphase Flow Over the cavitating high-speed torpedo. The cavitating flow over hemispherical and conical bodies indicate that the preconditioned system of equations converges rapidly to the required solution at very low speeds. To improve the understanding of the unsteady behaviour of supercavitating flows, Mostafa (2005) used a three-dimensional Navier-Stokes code to model the two-phase flow field around a hemisphere cylinder. The governing equations are discretized on a structured grid using an upwind difference scheme.

Supercavitating vehicles exploit supercavitation as a means to reduce drag and achieve an extremely high underwater speed. Supercavitation is achieved when a body moves through water at sufficient speed, so that the fluid pressure drops to the water vapor pressure. In supercavitating flows, a low-density gaseous cavity entirely envelops the vehicle and the skin drag of the vehicle is almost negligible. Hence, the vehicle can move at extremely high speed in a two-phase medium, Ahn (2007). So, A supercavitating torpedo is a complex high speed undersea weapon that is exposed to extreme operating conditions due to the weapon’s speed. Alyanak et al. (2006) formulates an optimize this problem to determines the general shape of the torpedo in order to satisfy the required performance criteria function of speed. Kamada (2005).

- 246 -
Mansour et al (2016) numerically compared between structured and unstructured grids and deduced the unstructured grid is more accurate than structured one in supercavitation simulation. They observed the trailing vortex in supercavitation appeared in the projectile wake.

The object of this work is to study the transit flow around either partially cavitating or supercavitating body affecting the high-speed underwater vehicles, which have different body shapes and cavitation numbers. Calculation will use structured grids and unstructured grids.

**NOMENCLATURE**

- $C_e, C_c$: phase change rate coefficients
- $D$: projectile diameter  [m]
- $f$: vapor mass fraction
- $L$: Projectile length  [m]
- $P$: turbulence kinetic energy  [m$^2$/s$^2$]
- $P_{sat}$: saturation pressure  [N/m$^2$]
- $P_{turb}$: magnitude of pressure fluctuations  [N/m$^2$]
- $P_t$: total pressure  [N/m$^2$]
- $R$: universal gas constant  [Nm/Kg.k]
- $R_e$: the rate of phase change
- $R_m$: Renold number
- $T$: fluid temperature  [K]
- $\Delta t$: physical time step  [second]
- $u, v, w$: velocity in x, y, w respectively  [m/s]
- $\nabla$: velocity vector
- $V_{ch}$: characteristic velocity $V_{ch} = \sqrt{\frac{\rho}{\rho_v}}$
- $W$: molecular weight  [kg/kg-mol]

**GREEK LETTERS**

- $\alpha$: vapor volume fraction
- $\sigma$: cavitation number $((p_{\infty} - p_v)/(1/2 \rho u^2))$  [N/m]
- $\rho_e$: the mixture density  [Kg/m$^3$]
- $\alpha_e$: effective exchange coefficient

**SUFFIXES**

- $c$: bubble reduction and collapse
- $e$: bubble generation and expansion
- $G$: gas phases
- $L$: liquid phases
- $V$: vapor phases

**2 THEORY BACKGROUND**

The calculation of cavitation phenomena in this paper is based on solving Navier-Stokes equations through cavitation module of ESI - CFD 2010 and $K-\varepsilon$ turbulence model. A numerical model previously developed by ESI-CFD to solve (Navier- Stokes) equations (Sighal, 1999).

As we know in cavitational flow as 2D flow, the mixture mass density ($\rho$) is function of vapour mass fraction ($f$), water density and vapour density. The $\rho$-$f$ relationship is:

$$\frac{1}{\rho} = f \frac{1}{\rho_v} + (1-f) \frac{1}{\rho_l}$$  \hspace{1cm} (1)

The previous equation can be written by using vapour volume fraction. Therefore, it is deduced from $f$ as follows:

$$\alpha = f \frac{\rho}{\rho_v}$$  \hspace{1cm} (2)

The transport equation for vapor is written as follows:
The expressions of $R_e$ and $R_c$ have been derived from the reduced form of the Rayleigh-Plesset equation (Hammitt, 1980), which describes the dynamics of a single bubble in an infinite liquid domain. The expressions for $R_e$ and $R_c$ are:

$$R_e = C_e \frac{V}{\rho} \rho \rho V \sqrt{\frac{2}{3} \frac{P_{sat} - P}{\rho}}$$

$$R_c = C_c \frac{V}{\rho} \rho \rho V \sqrt{\frac{2}{3} \frac{P_{sat} - P}{\rho}}$$

As we know that cavitation occurs in flow areas where flow velocity is very high or flow pressure is very low and approach to the water vapour pressure. The magnitude of pressure fluctuations is estimated by using the following empirical correlation (Hinze, 1975):

$$P'_{turb} = 0.39 \rho k$$

The phase-change threshold pressure value is as:

$$P'_{v, turb} = 0.5 P_{sat}$$

In this model due to low flow pressure, we put the dissolved (non-condensable) gases in cavitation calculations. However, the corresponding density (and hence volume fraction) varies significantly with local pressure. The perfect gas law is used to account for the expansion (or compressibility) of gas; i.e.,

$$\rho_{gas} = \frac{W}{RT}$$

The calculation of mixture density (equation 1) is modified as:

$$1 - \frac{f_v}{f_v} + \frac{f_g}{f_g} + \frac{1 - f_v - f_g}{\rho}$$

We have the following expression for the volume fractions of vapor ($\alpha_v$) and gas ($\alpha_g$):

$$\alpha_v = \frac{f_v}{f_v}$$

$$\alpha_g = \frac{f_g}{f_g}$$

and,

$$\alpha_l = 1 - \alpha_v - \alpha_g$$

The combined volume fraction of vapor and gas (i.e., $\alpha_l$) is referred to as the Void Fraction ($\alpha$). In practical applications, for qualitative assessment of the extent and location of cavitation, contour maps of void fraction ($\alpha$) are important.

3 EXPERIMENT SET-UP

Test-rig consists of tank filled with water and external support is seated above the tank, Fig. 1. The firing gone is fixed by the external support aligned with the water level. Four different shapes of projectile are used, Fig. 2. High-speed camera is used which has specifications of 1000 frame per seconds in movie recording. Each projectile is projected with speed of 55 m/s using the gun in water and the camera recorded the motion.

4 NUMERICAL ANALYSIS

In present research, supercavitation around projectile is simulated for four different projectile shapes. Hemisphere projectile has a hemispherical shape from both sides. Telescopic projectile is a telescopic shape at nose and flat shape at tail. Blunt projectile is a blunt shape at nose and flat shape at tail. Conical projectile is a conical shape at nose and flat shape at tail.
Four shapes of projectiles are numerically modelled by use two different grid designs, structured and unstructured. Thus, the used grids are structured mesh and unstructured mesh grids. The projectiles in numerical models are projected horizontally by speed 60 m/s in water. The figures from Fig.10 to Fig.27 show the numerical results for different projectiles nose shape which are moving from up to down in both structure and unstructured mesh.

Also, the projectile dimensions are related to D/L= 0.4. Comparison between two grids is performed. Table 1 shows the data of each grid. The table illustrates the number of cells, number of nodes, number of zones, and the time consumed to solve one time-step for each case.

### Table 1: Comparison between the two grids in mesh specifications for both projectiles.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Structured</th>
<th>Unstructured</th>
<th>Structured</th>
<th>Unstructured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemisphere</td>
<td>25,043</td>
<td>28,768</td>
<td>28,089</td>
<td>26,222</td>
</tr>
<tr>
<td>Telescopic</td>
<td>25,440</td>
<td>14,615</td>
<td>28,990</td>
<td>13,337</td>
</tr>
<tr>
<td>Zones</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Time (min)</td>
<td>0.5</td>
<td>0.1</td>
<td>2.5</td>
<td>2</td>
</tr>
</tbody>
</table>

The used computer for simulation the present study for both cases is a workstation with specifications:

- **Processor:** double Intel Xeon CPU E5-2620 v2 @ 2.10 GHz
- **Memory:** 16 GB

The transient cavitation flow analysis is computed for cavitation number of 0.0555. Used time-step interval is 1x10⁻⁵ sec.

### 5 RESULTS AND DISCUSSION

#### 5.1 EXPERIMENT RESULTS

Results show stages of supercavitation for hemispherical, telescopic, blunt, and conical projectiles, respectively.

**Fig. 7** shows the experimental shape of cavitation growth for the hemispherical nose projectile at different times from the shooting. The projectile is moved from up to down. The figure shows different six pictures. The first picture is taken at 0.556x10⁻⁵ sec after the shooting time and the projectile is shown in the right of the picture. The second picture is taken at time 1.12x10⁻⁵ second shows the cavity downstream the projectile. The third, fourth, and fifth are at times 1.668x10⁻⁵ sec, 2.224x10⁻⁵ sec, and 2.78x10⁻⁵ sec, respectively. Also, these three pictures show the gradual growth of supercavitation. The sixth picture is at time 3.336x10⁻⁵ sec and shows a trailing vortex in the wake of the projectile.

**Fig. 8** shows the experimental shape of cavitation growth for the telescopic nose projectile at different time relative to the shooting. The projectile is moved from up to down. The figure shows different six pictures. The first picture is taken at 0.556 x 10⁻⁵ sec relative to the shooting moment and the projectile is shown in the right of the picture. The second picture is taken at time 1.12 x 10⁻⁵ sec and shows the cavity downstream the projectile. The third, fourth, and fifth are at times 1.668 x 10⁻⁵ sec, 2.224 x 10⁻⁵ sec, and 2.78 x 10⁻⁵ sec, respectively. Also, these three pictures show the gradual growth of supercavitation. The sixth picture is at time 3.336 x 10⁻⁵ sec and shows a trailing vortex in the wake of the projectile.

**Fig. 9** shows the experimental shape of cavitation growth for the blunt nose projectile at different time relative to the shooting. The projectile is moved from up to down. The figure shows different seven pictures. The first picture is taken at 0.556 x 10⁻⁵ sec relative to the shooting moment and the projectile is shown in the right of the picture. The second picture is taken at time 1.12 x 10⁻⁵ sec and shows the cavity downstream the projectile. The third, fourth, and fifth are at times 1.668 x 10⁻⁵ sec, 2.224 x 10⁻⁵ sec, and 2.78 x 10⁻⁵ sec, respectively. Also, these three pictures show the gradual growth of supercavitation. The sixth picture is at...
time 3.336 x10$^5$ sec and shows a trailing vortex in the wake of the projectile. The seventh picture also shows clear trailing vortex at time 3.892 x 10$^5$ sec.

5.2 NUMERICAL RESULTS

5.2.1 HEMISPHERE PROJECTILE

Hemisphere projectile is hemispherical projectile from two sides. The structured grid for this projectile is used as shown in Fig.3a. The structure grids are divided into three zones. Unstructured grid of the projectile, shown in Fig.3b, is performed in one zone domain. The grids are clustered near the body to solve the boundary layer. The physical time step is taken to be 1x10$^5$ second for the unsteady flow computations in order to resolve accurately the transients of the supercavitating flow. Figs.10 and 11 display the iso-density contours for cavitating flow over both grids of hemispherical body in a time sequence of the bubble shape growth. This hemisphere projectile has half spheres from both sides at diameter 0.4 L. The cavitation number is $\sigma$ = 0.0555 at speed of $u$ = 60 m/s. It is demonstrated that the cavity formation has five stages. First, a cavity starts to grow at the wake of the body only due to its low pressure. At the second stage, another cavity grows beside the nose while the cavity at the body wake continues to grow. The cavity beside the nose grows enough to affect the pressure at the body wake, so, the cavity at the body wake starts to collapse at the third stage. In the fourth stage, the cavity beside the nose grows enough to merge with the cavity at the body wake. Finally, that cavity starts to have a fluctuation around the final shape.

Also, Figs.18 and 19 represent the distribution of void fraction, total pressure, static pressure and velocity magnitude for this projectile. The void fraction contour is approximately similar to the iso-density contours as well as the iso-total pressure contours. There is a reverse flow in the horizontal velocity component at the cavities region near to the body in the body wake region. The maximum vertical velocity component is concentrated around the front nose. In this case, the maximum turbulence kinetic energy is around the front nose similar to the iso-pressure contour.

5.2.2 TELESCOPIC PROJECTILE

Telescopic projectile has telescopic shape at nose and flat at tail. The structured grid for this projectile is designed as shown in Fig.4a where the structured mesh is refined by dividing the domain to 3 zones. Unstructured grid of this projectile, shown in Fig.4b, is performed in one zone domain. The grids are clustered near the body to solve the boundary layer. The physical time step is taken to be 1x10$^5$ second for the unsteady flow computations in order to resolve accurately the transients of the supercavitating flow. Figs.12 and 13 display the iso-density contours for cavitating flow over both grids of telescopic body in a time sequence of the bubble shape. This telescopic projectile has telescopic nose shape from one side at diameter 0.4 L and total length 0.2 L. The cavitation number is $\sigma$ = 0.0555 at speed of $u$ = 60 m/s. It is demonstrated that the cavity formation has five stages. First, a cavity starts to grow at the wake of the body only due to its low pressure. At the second stage, another cavity grows beside the nose while the cavity at the body wake continues to grow. The cavity beside the nose grows enough to affect the pressure at the body wake, so, the cavity at the body wake starts to collapse at the third stage. In the fourth stage, the cavity beside the nose grows enough to merge with the cavity at the body wake forming a large one. Finally, that cavity starts to have a fluctuation around the final shape.

Figs.20 and 21 represent the distribution of void fraction, total pressure, pressure and velocity magnitude. Also, void fraction contour is approximately similar to the iso-density contours as well as the iso-total pressure contours. There is a reverse flow in the horizontal velocity component at the cavities region near to the body and in the body wake. The maximum vertical velocity component is concentrated around the front nose. In this case, the maximum turbulence kinetic energy is around the front nose similar to the iso-pressure contour.

5.2.3 BLUNT PROJECTILE

Blunt projectile is flat-nose projectile and flat at tail. The structured grid for this projectile is used as shown in Fig.5a. Structured mesh is refined but by dividing the domain to 3 zones.
Unstructured grid of the projectile, shown in Fig.5b, is performed in one zone domain. The grids are clustered near the body to solve the boundary layer. The physical time step is taken to be 1x10^{-5} second for the unsteady flow computations in order to resolve accurately the transients of the supercavitating flow.

Figs. 14 and 15 display the iso-density contours for cavitating flow over both grids of blunt body in a time sequence of the bubble shape. This hemisphere projectile has blunt shape from both sides at diameter 0.4 L. The cavitation number is $\sigma = 0.0555$ at speed of $u= 60$ m/s. It is demonstrated that the cavity formation has five stages. First, a cavity starts to grow at the wake of the body only due to its low pressure. At the second stage, another cavity grows beside the nose while the cavity at the body wake continues to grow. The cavity beside the nose grows enough to affect the pressure at the body wake, so, the cavity at the body wake starts to collapse at the third stage. In the fourth stage, the cavity beside the nose grows enough to merge with the cavity at the body wake forming a large one. Finally, that cavity starts to have a fluctuation around the final shape.

Figs.22 and 23 represent the distribution of void fraction, total pressure, pressure and velocity magnitude. Also, void fraction contour is approximately similar to the iso-density contours as well as the iso-total pressure contours. There is a reverse flow in the horizontal velocity component at the cavities region near to the body and in the body wake. The maximum vertical velocity component is concentrated around the front nose. In this case, the maximum turbulence kinetic energy is around the front nose similar to the iso-pressure contour.

5.2.4 CONICAL PROJECTILE

Conical projectile is conical-nose projectile and flat at tail. The structured grid for this projectile is used as shown in Fig.6a. Structured mesh is refined but by dividing the domain to 3 zones. Unstructured grid of the projectile, shown in Fig.6b, is performed in one zone domain. The grids are clustered near the body to solve the boundary layer. The physical time step is taken to be 1x10^{-5} second for the unsteady flow computations in order to resolve accurately the transients of the supercavitating flow. Figs.16 and 17 display the iso-density contours for cavitating flow over both grids of conical body in a time sequence of the bubble shape. This conical projectile has cone base at diameter 0.4 L and 0.2 L in cone height. The cavitation number is $\sigma = 0.0555$ at speed of $u= 60$ m/s. It is demonstrated that the cavity formation has five stages. First, a cavity starts to grow at the wake of the body only due to its low pressure. At the second stage, another cavity grows beside the nose while the cavity at the body wake continues to grow. The cavity beside the nose grows enough to affect the pressure at the body wake, so, the cavity at the body wake starts to collapse at the third stage. In the fourth stage, the cavity beside the nose grows enough to merge with the cavity at the body wake forming a large one. Finally, that cavity starts to have a fluctuation around the final shape.

Figs.24 and 25 represent the distribution of void fraction, total pressure, pressure and velocity magnitude. Also, void fraction contour is approximately similar to the iso-density contours as well as the iso-total pressure contours. There is a reverse flow in the horizontal velocity component at the cavities region near to the body and in the body wake. The maximum vertical velocity component is concentrated around the front nose. In this case, the maximum turbulence kinetic energy is around the front nose similar to the iso-pressure contour.

5.3 COMPARISONS AND OBSERVATIONS

In Figs 26-b, 27-b, 28-b and 29-b which represent velocity vectors distribution in flow around projectiles in unstructured mesh modelling, there is a new observation in supercavitation phenomena which existence of a vortex in the tail area. This vortex is in agreement with actual (experimental) case. These results aren’t clear in case of structured grid shown in Figs 26-a, 27-a, 28-a and 29-a.

6 SUMMARY AND CONCLUSIONS

Using high-speed camera of 1000 fps is useful and effective in study the supercavitation. Also, present experimental and numerical works are valid and agree each other.
The unsteady flow around either partially cavitating or supercavitating high-speed underwater vehicles is simulated. Also, the accuracy of results is affected by grid design.

There are five stages for the cavities formation. First, a cavity starts to grow at the wake of the body only due its low pressure. At the second stage, another cavity grows beside the nose while the cavity at the body wake continues to grow. The cavity beside the nose grows enough to affect the pressure at the body wake, so, the cavity at the body wake starts to collapse at the third stage. In the fourth stage, the cavity beside the nose grows enough to merge with the cavity at the body wake forming a large one. Finally, that cavity starts to fluctuate around the final shape.

There is a reverse flow in the horizontal velocity component at the cavities region near to the body and in the body wake. The maximum vertical velocity component is concentrated around the front nose.

New note is observed which is finding a vortex in the nose area by using unstructured grid of telescopic projectile. This vortex is in agreement with actual (experimental) case of Mostafa et al. (2001). The results by structured mesh grid did not show this vortex.

Using unstructured grid is better than structured one for water-flow simulation of supercavitation for hemispherical, telescopic, blunt and conical nose projectile shapes.

From the experimental projection movies of blunt-nose projectile, it is clear that the wake cavity collapse is similar to that collapse get from numerical simulation by unstructured mesh. This indicates that the unstructured mesh is more accurate in numerical modelling than structured one.

Using ESI-CFD commercial code is valid for simulating supercavitation around projectiles in water.

REFERENCES:


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<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
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<tbody>
<tr>
<td>(1)</td>
<td>Experiment Set-up.</td>
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<tr>
<td>(2)</td>
<td>Four shapes of projectiles.</td>
</tr>
<tr>
<td>(3)</td>
<td>Grid over hemisphere projectile.</td>
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<tr>
<td>(4)</td>
<td>Grid over telescopic projectile.</td>
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<tr>
<td>(5)</td>
<td>Grid over blunt projectile.</td>
</tr>
<tr>
<td>(6)</td>
<td>Grid over conical projectile.</td>
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</table>
Fig. (7) Pictures of growth of cavitation for Hemispherical-nose projectile. The projectile moves from up to down. The times of pictures are $0.556 \times 10^{-5}$ sec, $1.12 \times 10^{-5}$ sec, $1.668 \times 10^{-5}$ sec, $2.224 \times 10^{-5}$ sec, $2.78 \times 10^{-5}$ sec, $3.336 \times 10^{-5}$ sec, respectively.
Fig. (8) Pics of growth of cavitation for Telescopic-nose projectile. The projectile moves from up to down. The times of pictures are $0.556 \times 10^{-5}$ sec, $1.12 \times 10^{-5}$ sec, $1.668 \times 10^{-5}$ sec, $2.224 \times 10^{-5}$ sec, $2.78 \times 10^{-5}$ sec, $3.336 \times 10^{-5}$ sec, respectively.
Fig. (9) Pics of growth of cavitation for blunt-nose projectile. The projectile moves from up to down. The times of pictures are $0.556 \times 10^{-5}$ sec, $1.12 \times 10^{-5}$ sec, $1.668 \times 10^{-5}$ sec, $2.224 \times 10^{-5}$ sec, $2.78 \times 10^{-5}$ sec, $3.336 \times 10^{-5}$ sec, $3.892 \times 10^{-5}$ sec, respectively.
Fig. (10): Supercavitating cavities formation upon hemisphere projectile at speed 60 m/s, using structured mesh domain.

Fig. (11): Supercavitating cavities formation upon hemisphere projectile at speed 60 m/s, using unstructured mesh domain.
Fig. (12) Supercavitating cavities formation upon telescopic projectile at speed 60 m/s, using structured mesh domain.

Fig. (13) Supercavitating cavities formation upon telescopic projectile at speed 60 m/s, using unstructured mesh domain.
| a) Density distribution at t=1x10^{-5} sec |
| b) Density distribution at t=50x10^{-5} sec |
| c) Density distribution at t=100x10^{-5} sec |
| d) Density distribution at t=300x10^{-5} sec |
| e) Density distribution at t=500x10^{-5} sec |
| f) Density distribution at t=800x10^{-5} sec |
| g) Density distribution at t=1200x10^{-5} sec |
| h) Density distribution at t=2000x10^{-5} sec |
| i) Density distribution at t=3000x10^{-5} sec |

**Fig. (14):** Supercavitating cavities formation upon blunt projectile at speed 60 m/s, using structured mesh domain.

**Fig. (15):** Supercavitating cavities formation upon blunt projectile at speed 60 m/s, using unstructured mesh domain.
Fig. (16): Supercavitating cavities formation upon conical projectile at speed 60 m/s, using structured mesh domain.

Fig. (17): Supercavitating cavities formation upon conical projectile at speed 60 m/s, using unstructured mesh domain.
Fig. (18): Flow condition around hemisphere projectile using structured grid at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $Re=306 \times 10^6$, and $t=0.014$ sec.

Fig. (19): Flow condition around hemisphere projectile using unstructured grid at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $Re=306 \times 10^6$, and $t=0.014$ sec.

Fig. (20): Flow condition around telescopic projectile using structured grid at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $Re=306 \times 10^6$, and $t=0.014$ sec.

Fig. (21): Flow condition around telescopic projectile using unstructured grid at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $Re=306 \times 10^6$, and $t=0.014$ sec.
Fig. (22) Flow condition around blunt projectile using structured grid at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $\text{Re}_n=306 \times 10^6$, and $t=0.014$ sec.

Fig. (23) Flow condition around blunt projectile using unstructured grid at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $\text{Re}_n=306 \times 10^6$, and $t=0.014$ sec.

Fig. (24) Flow condition around conical projectile using structured grid at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $\text{Re}_n=306 \times 10^6$, and $t=0.014$ sec.

Fig. (25) Flow condition around conical projectile using unstructured grid at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $\text{Re}_n=306 \times 10^6$, and $t=0.014$ sec.
Fig. (26): velocity vectors for hemispherical projectile using structured and unstructured grids at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $Re=306 \times 10^6$, and $t=0.014$ sec.

Fig. (27) velocity vectors for telescopic projectile using structured and unstructured grids at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $Re=306 \times 10^6$, and $t=0.014$ sec.
Fig. (28) velocity vectors for blunt projectile using structured and unstructured grids at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $Re_n=306 \times 10^6$, and $t=0.014$ sec.

Fig. (29) velocity vectors for conical projectile using structured and unstructured grids at supercavitating condition: $\sigma=0.0555$, $u=60$ m/s, $Re_n=306 \times 10^6$, and $t=0.014$ sec.