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CFD Based Shape Optimization of Axisymmetric Cavitators in Supercavitating Flows

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Abstract. Supercavitation is a hydrodynamic behavior, which leads to a drastic reduction in hydrodynamic drag by allowing the bodies to travel inside a self-generated bubble of water vapor or gas. The world's major navies are developing entire arsenals of totally new high-speed underwater weapons based on the physical phenomenon of supercavitation. This research concentrates the shape of the cavitator optimization by means of numerical investigation. The shapes of the axisymmetric cavitators like disc, hemispherical, conical and edged double conical were considered with the same diameter. The modeling and CFD analysis were conducted in ANSYS Fluent 16.0. The RNG K-epsilon turbulence model used to evaluate the performance of various shapes of the axisymmetric cavitators. The Contours of Density (Mixture), the Contours of Volume Fraction (Water) and the Contours of Volume Fraction (Vapor) considered for comparison and resulted length of supercavity is used to optimize the shape.

INTRODUCTION

Cavitation is a phenomenon of formation of vapor bubbles in liquids due to reduced local or free stream pressure (P0) to closure to saturation vapor pressure (Pb). The other governing parameters are (refer equation (1)): the cavitation number (Kc), free stream velocity (V0), the density of the liquid (ρ). The equation (2) defines the Cpm which is pressure coefficient when the Pbequal to Pm (minimum pressure) and the an incipient cavitation number presented in the equation (3).

$$\mathrm{Kc} = \frac{\mathrm{P_0 - P_b}}{\frac{1}{2}\rho \mathrm{V_0^2}} = 1.0 \qquad (1)$$

$$\mathrm{Cpm} = \frac{\mathrm{P_m - P_0}}{\frac{1}{2}\rho \mathrm{V_0^2}} \qquad (2)$$

$$\mathrm{Ki} = -\mathrm{Cpm} \qquad (3)$$

If $K < Ki$ means there is no cavitation effect, suppose $K > Ki$ causes the noise and vibration.

When the cavitation number is very low ($K \leq 0.1$), a large cavity can attach to a solid boundary called supercavitation. When the super-cavitation occurs, the drag of the body surrounded by the cavity can be greatly reduced. This is because the friction drag, which depends on the viscosity of the fluid, is lowered due to the

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vaporous pocket surrounding the body. In real world application, a bubble is created an undersea with gas filled enough to travel through liquid and a cavitator mounted at the forward end. If the cavitation grows in a way to envelope the whole body, then this type of cavitation is referred to as supercavitation. Supercavitation is desirable to achieve viscous drag reduction on underwater vehicles operating at high speeds. Other than viscous drag reduction, lift force acting on hydrofoils can be increased by creating a super cavity on the upper surface at constant pressure. There is couple of ways to maintain the supercavity such that results of achieving high speed, the water start to vaporizesnear the nose of the body called Natural Cavitation. The next one is artificial cavitation in which gas is applied to the cavity at ambient pressure. The foremost calculation for the dimensions of an axi-symmetric cavity was carried out by Garabedian (1956). His theory was derived using asymptotic relations while assuming a steady, axially symmetric, ir-rotational flow of an incompressible liquid. This model has a symmetrically shaped nose and tail. Garabedian formulas for the dimensions of a cavity created by a disk are,

$$\text{Lcavity} = \text{Dc}\,\frac{\sqrt{C_d}}{K}\sqrt{\ln\frac{1}{K}} \tag{4}$$

$$\text{Dcavity} = \text{Dc}\,\frac{\sqrt{C_d}}{K} \tag{5}$$

$$\text{Cd} = \text{Cd0}\ (1+K) \tag{6}$$

Where Dc is the cavitator disk diameter, D cavity is the diameter of cavity, L cavity is the length of the cavity, Cd is the coefficient of drag, Cd0 is the coefficient of drag when the cavitation number equals to zero. A typical application is show in the Figure 1 for easy understanding.

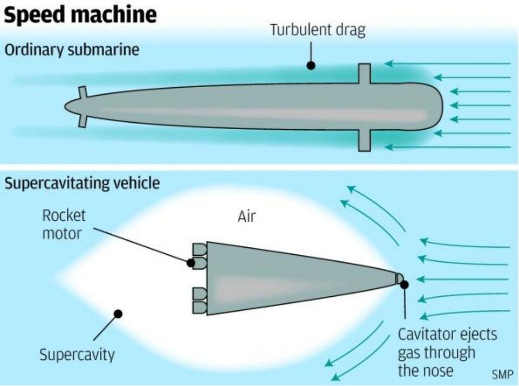


FIGURE 1. Supercavitating with spherical cavitator.

choice of size and shape of the cavitator or supercavitating vehicles, plays important role in the supercavitation studies. The cavitator size ensures cavity formation nearby nose of the axi-symmetric body clearly. The smaller the diameter of cavitator is most preferable. In this research flat disc, hemispherical, conical and double wedged conical type axisymmetric cavitators considered with same diameter.

LITERATURE REVIEW

Byoung-Kwon Ahn et al. investigate the disk type axisymmetric cavitator and analysed the supercavity generated behind it. The authors examined the Cavitation parameters[1]. Yunhua Jiang et al examined steady flow characteristics of the ventilated super cavity which generated by gas jet cavitator[2]. Siyao Shao et al conducted comparative study of specified case of supercavitation formed by both natural and ventilated across two closed-wall water tunnel facilities[3]. Xue-weiZHANGet al. reported that in both natural and ventilated cases the supercavitivy shape and dimensions are retaively same when the cavitation number is small and equal [9].Ye-junGONGet al, considered the circular disk and cone cavitator in their studies to investigate the Numerical investigation of the effect of rotation on cavitating flows over axisymmetric cavitators[4]. They considered different K (K= 0.15, 0.175, 0.2, 0.225 and 0.25) for validation of the effects.Chen-Xing Jianget al studied with help of CFD that the influence of drag-reduction additives in the ventilated supercavitation and reported that they are influencing in friction drag before completion of supercavity formation and their reduction rate two phase and three phase flows are 49.66% and 58.13% respectively[5]. R. Shafaghat et al used the Multi-objective optimization by using NSGA II algorithm for optimizing the shape of the axisymmetricvcavitator in Supercavitation flow and examined at two dimensional flow[6] ,[7]. Mohammad-Reza Pendaretal,Investigated with help of numerical analysis the correlation between the length and diameter of hemispherical head in cavitation and supercavitation for relatively small cavitation numbers like 0.07, 0.05, 0.02. The authors used both mass transfer and turbulencemodels and reported that the re-entrant jet behaviour and boundary layer separation play important role in the bubble shedding in particularly at cavity closure region [8]. Byoung-Kwon Ahnet al investigated by means of numerical studies on conical cavitator with different wedge angle, and studied the influence of cavitation number for single cavitator and reported that decrease of cavitation number increases the cavity length[10]. Young KyunKwack et al, considers the conical and disk cavitator for numerical studies on cavitation. The author used Standard K-Epsilon (SKE) turbulent model and varied the cavitation number from 0.1 to 1 with constant 2 atm pressure and concluded that the supercavitation decreases the drag of the vehicle considerably and ensured that if the cavitation number increase the supercavitation length decreases irrespective of cavitatorshape[11]. In this research flat disc, hemispherical, conical and edged double wedge conical type cavitators considered for the study with constant diameter of the cavitator with other conditions remains same.

Materials and Methods

Numerical solver settings are the primary for modeling and analysis. The followings are the details.

Pressure based algorithm

Pressure based algorithm can be employed to solve this kind of problems. Simulation of such pressure based algorithm for conserving the mass unlike real gas simulation model or simulation with non reflecting boundary conditions.

Turbulence model

Turbulence modeling is required to calculate many flow fields. The majority of the flow is turbulent, so the ANSYS software has always special emphasis on providing leading turbulence models to capture the effect of turbulence accurately and efficiently. In this research, the RNG K-epsilon turbulence model is employed for simulating the mean flow characteristics under the turbulence flow conditions, and the viscous heating effect is also taken in to consideration.

Multiphase Model

The multiphase flow model is to be considered for this analysis because the sea water and gas are involved in this analysis. So this research preferred the multi phase mixture model in FLUENT and such model is used to predict the cavity formation.

Material Selection

Selection of material in fluent is very important. By default material list air will be acting as a fluid but our research mixture material properties needed. Mixture proper material will not exist in local list, for that, first enable the required number of phases. In the current research two phases are required.

- Primary Phase: Seawater
    a) Depth or submersion (h) : 15 meter
    b) Density : 1024 kg/m^3
    c) Local Pressure : 252102 N/m^2
    d) Viscosity : 0.0010268 kg/m.s
- Secondary Phase: Vapor
    a) Density : 0.0193 kg/m^3
    b) Vapor Pressure : 2591 N/m^2
    c) Viscosity : 0.00001 kg/m.s

Boundary Conditions

For this Computational fluid dynamics (CFD) analysis the following boundry conditions were set.

Simulation Type : unsteady
Model : Axi-Symmetric
Inlet : Velocity Inlet (69.8 m/s)
Outlet : Pressure Outlet
Cavitation Disk : Wall (Diameter: 3mm)
Upper section : Wall
Inner lines : Interior
Centre line : Axis

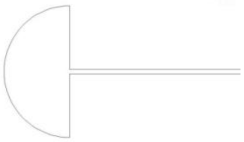
CAVITATION MODEL

By enabling the cavitation model in the fluent, we can simulate and analyze the phase change, bubble dynamics and turbulence fluctuations in the flow field. It has a capability to account the multiphase flows. The cavitation model is used without considering the slip velocity between the phases. This analysis is done at the cavitation number of 0.1 and the saturation vapor pressure calculated from the steam table and entered in the cavitation dialog box to start the phase change.

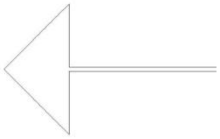
Numerical Scheme

The coupled scheme is used for pressure-velocity coupling and the flow equations are solved in the first and second order.

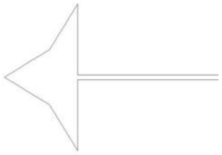
(a)Flat Disc



(b) Hemispherical



(c) Conical



(d) Double Wedged Conical

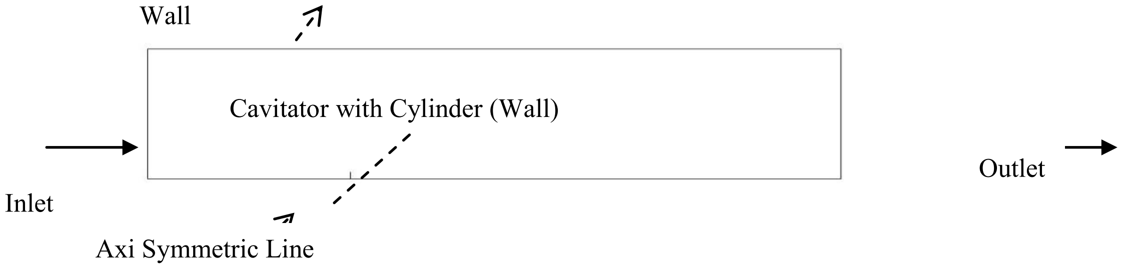


FIGURE2. Domain with Cavitator (Axi Symmetric)

FIGURE3. Domain with Flat Disc Cavitator Model

CFD Analysis

The four types of Cavitators considered for investigation namely flat disc, hemispherical, conical and double wedged conical type. All the cavitator is considered in the position such a way that axis on the Axi Symmetric Line. The rough sketch of such four cavitators shown in the figure 2. The figure 3 illustrates the common domain of the study. The ANSYS Fluent Release 16.0 employed for modeling and CFD analysis of supercavitation effects by all these four cavitators. The results are discussed in the next section.

RESULTS AND DISCUSSIONS

The CFD analysis for different cavitators like flat disc, Hemispherical, conical and double wedged conical with same diameters of 3mm, were carried out with cavitation number K =0.1 and Reynolds number of $1.66*10^5$forturbulence condition. The Cavitation starts to form behind the disk with two low pressure regions one over another. The pressure and vapour pressure maintains constant. The simulated results cavitator wise presented from figure 4 to figure 15. It is noticed that at the velocity of 69.8 m/s the steady supercavity was formed in all the cases. The super cavity lengths obtained from the simulated results were tabulated in the table1.

Case 1: Flat Disc Cavitator

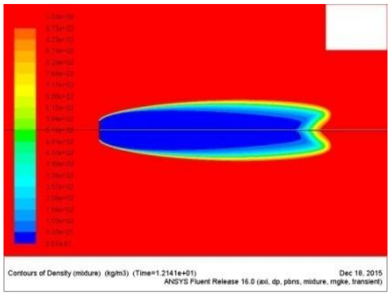


FIGURE 4. Contours of Density (Mixture)

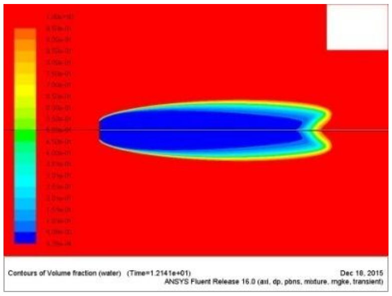


FIGURE5. Contours of Volume Fraction (Water)

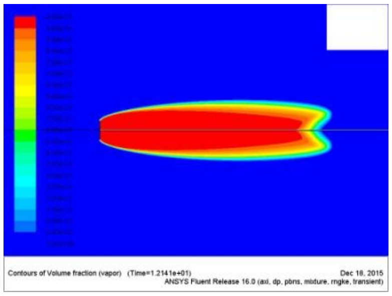


FIGURE 6. Contours of Volume Fraction (Vapor)

Case 2: Hemispherical Cavitator

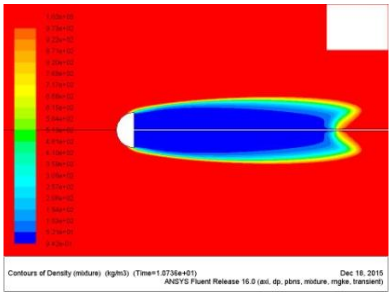


FIGURE 7. Contours of Density (Mixture)

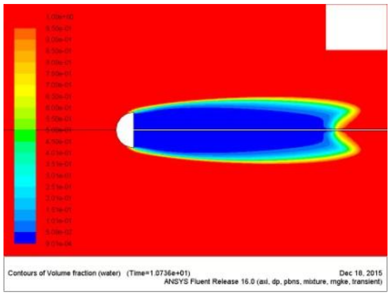


FIGURE 8. Contours of Volume Fraction (Water)

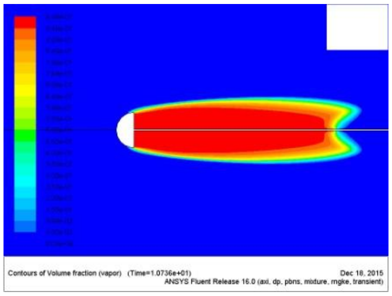


FIGURE 9. Contours of Volume Fraction (Vapor)

Case 3: ConicalCavitator

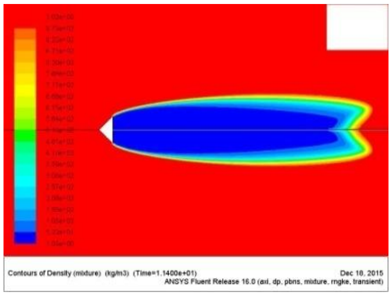


FIGURE 10. Contours of Density (Mixture)

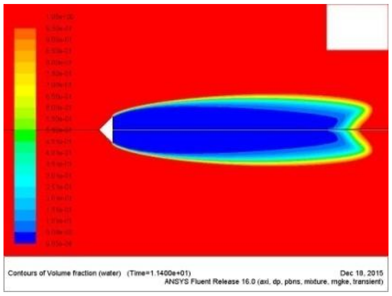


FIGURE 11. Contours of Volume Fraction (Water)

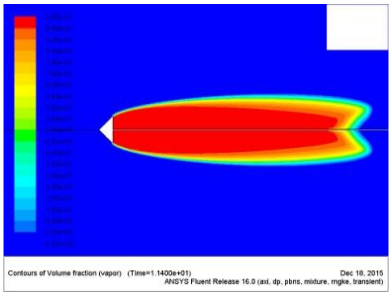


FIGURE 12. Contours of Volume Fraction (Vapor)

Case 4: Double Wedged Conical Cavitator

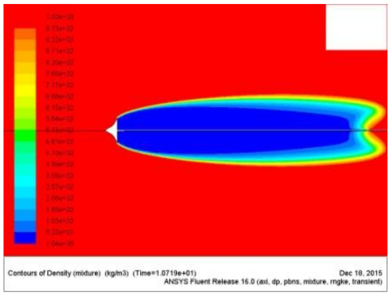


FIGURE 13. Contours of Density (Mixture)

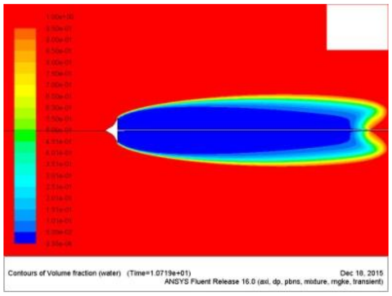


FIGURE 14. Contours of Volume Fraction (Water)

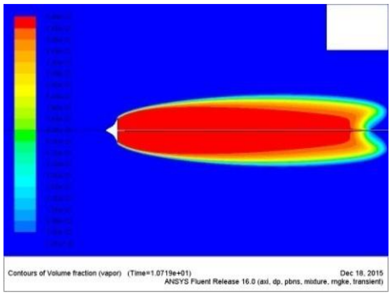


FIGURE 15. Contours of Volume Fraction (Vapor)

TABLE 1. Length of supercavitation for different cavitator shape

S.No	Cavitator Shape	D $_{\text{Cavitator}}$(mm)	Length of supercavitation(mm)
1	Flat Disk	3.0	39.36
2	Sphere		22.66
3	Cone		32.02
4	Double Wedged Cone		36.75

CONCLUSION

Numerical investigation for optimizing the shape of the axisymmetric cavitator is presented in this paper. The four axisymmetric cavitators with different shaped such as disc, hemispherical, conical and edged double conical with same diameter were analyzed well. The supercavitation shape probably lengths were obtained from The Contours of Density (Mixture), the Contours of Volume Fraction (Water)and the Contours of Volume Fraction (Vapor). The spherical shaped axisymmetric cavitators produces supercaivity with minimal length of 22.66 mm than other shapes.

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