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Numerical Analyses for Improved Terminal Velocity of Deep Water Torpedo Anchor

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ABSTRACT

Torpedo anchor is an innovative anchor solution for deep water applications. Typically, the anchor is released from a drop height of greater than 50 meters from seabed, and eventually penetrates into the seabed through free fall. As global offshore oil and gas exploration and production activities are now leaning towards regions with deeper sea death, there is a need for the anchor to achieve higher terminal velocity before impact so as to achieve deeper penetration with greater holding capacity. Literature review showed that there is a lack of research data available for improvement on terminal velocity itself. Furthermore, there is no established guideline for the designs of torpedo anchors. This research aims to investigate the effects of manipulation of torpedo's geometries in order to attain higher terminal velocity. The parameters of interest include geometric changes of the original design, as well as sea water properties that reflect water depth in South China Sea. Besides, new design features are proposed and investigated in the overall parametric studies. It was found that the terminal velocity can be improved by sharper tip angle, greater aspect ratio, greater diameter ratio, and an optimum rear angle at 30°. Sensitivity of drag coefficient towards each of the parameters is established in this paper.

Keywords: Drag coefficient, hydrodynamics, terminal velocity, subsea, deep water technology, torpedo anchor, offshore.

1. INTRODUCTION

Increasing number of offshore explorations activities are being conducted in deep water Malaysia where water depth exceeds 1000 m. In deep sea regions, the floating structures such as floating production storage & offloading unit (FPSO) and mobile drilling unit (MODU) must be anchored with robust mooring system. These anchorage solutions are such as the Suction Caisson Anchors, Vertical Loaded Anchors (VLA), Suction Embedded Plat Anchors (SEPLA) and Torpedo Anchors. Among them, the torpedo anchor, which was initially developed and patented by Petrobras in year 1996, has several advantages over the others. For instance, torpedo anchors are highly economical because no external energy is required for its installation (Hasanloo and Yu, 2011). Besides, it was found that the deployment of torpedo anchors is much easier and faster as compared to similar solutions such as VLA and suction piles (Brandão et al., 2006). In essence, torpedo anchorage system has competitive edge in terms of cost reduction and simplified installation (Ehlers et al., 2004). Its applications are also less affected by increasing water depth as compared to conventional anchoring concepts (Medeiros, 2002).

Typical sizes of torpedo anchors range from 10-20 meters in height and 0.325-1.2 meters in diameter. A single unit of torpedo anchor can have a dry weight of 40-100 tons. It is released from an installation vessel via a simple pulley system towards the seabed till a drop height of approximately 50 meters is reached. Then, it will be released to fall vertically downward by gravitational pull. Through the free fall period, the anchor is able to achieve a very high speed, and subsequently penetrates into the seabed. However, there exists a threshold speed for torpedo anchor regardless of the drop height (Lieng, 2001). This point occurs when the downward acceleration is equal to zero. This particular speed limit is known as the terminal velocity. According to Raie and Tassoulas (2009), higher terminal velocity will consequently provide greater holding capacity for the platforms, by resulting in deeper penetration. This finding is in line with the results of tests conducted by Hasanloo et al. (2009).

The achievable threshold speed during the free fall phase of torpedo anchor has to be pushed forward for many future applications. However, there is a lack of research conducted for improvement on the terminal velocity during the anchor drop down. Besides, there is no well-established guideline developed for the designs of torpedo anchors.

Fernandes et al. (2006) conducted small scale laboratory tests by using scaled torpedo anchors according to their design ratio. It was determined that presence of rear lines could increase the drag acting against torpedo anchor while it is travelling vertically downward. Moreover, the absence of pulley can further reduce the drag, thus result in higher kinetic energy gained by the anchor. Besides, according to Hasanloo and Yu (2011), there is a minimum weight required for the anchor to fall steadily at different water depth. At the same time, density of the anchor was found to have positive impact on its travelling velocity. On the other hand, aspect ratio is identified to have direct influence on the drag coefficient of cylindrical prototypes, utilized by the European Nuclear Energy Agency to study the feasibility of disposal of radioactive waste through free fall cylindrical projectiles into oceanic sediments (Hasanloo and Yu, 2011). The relationship was categorized as followed

$$0.030 + 0.0085\,(L/D) < C_d < 0.039 + 0.0109\,(L/D), \tag{1}$$

where L is the length of the torpedo, D its diameter and C_d is the drag coefficient. Furthermore, it was concluded that the embedment depth of torpedo anchor is directly proportional to its impact velocity (O'Loughlin et al., 2004). The dependence of impact velocity on its geometry and mass are analyzed too. On the other hand, it was shown implicitly that embedment depth of torpedo anchor is dependent on its terminal velocity (Raie, 2009); the variation of tip was illustrated too, but the resulting impact on its terminal velocity was not examined. CFD procedures were proposed for 3 major phases that the torpedo anchor will encounter, namely its installation, set-up by consolidation of soil, and pull out as reported by Raie (2009).

Recently, Hasanloo et al., (2012) used 7 prototypes of torpedo anchors with different densities, aspect ratio, scale ratio, and fin sizes to study their influence on falling velocity during acceleration. As a result, the relationship between drag coefficient, C_d and Reynolds number, Re, was plotted.

For sea water properties, the viscosity ranged from approximately 0.0010 N.s/m^2 to 0.0015 N.s/m^2 when water depth increases from 100 meters to 2000 meters (Murray, 2004). While sea water density changes from 1024 kg/m^3 to 1028 kg/m^3 within the same range of ocean depth. There were field tests being conducted to test the feasibility of using torpedo anchors for FPSO. It was found that torpedo anchor is well suitable for mooring of large FPSO in deep water; in this case it is the P-50 mooring system (Brandão, 2006). Specifically, a total of 10 units of T-98 torpedo anchors were used in this mooring system to provide necessary holding capacity for the floating structure. The T-98 torpedo design was done purposely for this FPSO operating in water depth of 1240 meters, in the Albacora Leste Field located in the Campos Basin, Brazil. According to [3], this T-98 design has a total mass of 98 metric tons, diameter of 1.07 meters, and length of 17 meters with 4 wings to ensure its directional stability. Table 1 summarized the dimensions and specification of torpedo anchors reported in the open literature and it is immediately obvious that the two gaps of missing information is the maximum achievable terminal velocity and penetration depth.

This research aims to propose designing methods for attaining higher terminal velocity. Besides, as the coefficient of drag is the determining factor for terminal velocity, correlations between geometric changes and its resulted drag coefficient will be developed.

Ref.	Dry weight (kN)	Dia. (m)	Length (m)	Aspect ratio (L/D)	Term velocity (m/s)	Penetration depth (m)	Application	Remarks
Beck & Vandenworm, (2011)						9	Research	
	17.66			30		30		
Brandao et al. (2006)	421.83						Model T-43	
	961.38	1.07	17	15.89			Model T-98	4 wings: 0.9m x 10m
	740	1.2	13	10.83			DPA	
Brandao et al. (2006); Ehlers et al (2004)	961	1.07	17				FPSO (Depth 1400 m)	Holding capacity 7500 kN
Colliat (2002)		0.0175	0.135	7.71				
	400	0.76	12	15.79		29	Marlim Field Test	Drop height 30m
Ehlers et al. (2004)	240	0.76	12	15.79			Campos Basin	Without fins
Colliat (2002)	620	1.07	12	15.79				
	961	1.07	17	15.79			FPSO	
Fernandes et al. (2006)	17.66	0.34	3.25	10	50		European Standard Penetrator	
Hasanloo et al. (2012)	240	0.76	12	15.79			3 risers of 12"D, depth 1300m	Holding capacity 1400 kN
	620	0.76	12	15.79			Campos Basin	Water depth 200-1000m
		1.07	12	11.25			Campos Basin	Water depth 200-1000m
		0.76 - 1.01					MODU	Water depth: up to 2000m
Kunitaki et al. (2008)		0.762 – 1.07	11.89 – 14.94	Holding capacity: 1334-8896 kN			Free fall height 30 – 152 m	Models patented by Petrobras (1996)

Table 1. Summary of dimensions specification of torpedo anchor in open literature

2. METHODOLOGY

The present research involves extensive use of FLUENT for computational fluid dynamics simulations. The working fluid is a model of sea water, and the type of fluid flow is set to be turbulent due to the high velocities involved. Thus, $k-\varepsilon$ solver is most suitable to be used (Raie, 2009). Several assumptions are made such as the sea water is modeled as incompressible Newtonian fluid. This is in line with the fact that the Mach number is lesser than 0.3 with the velocities of flow studied in this context. The changes in temperature with increasing depth are neglected. The horizontal velocity of fluid flow is assumed to be zero in comparison to the vertical free fall velocity of the anchor. Consequently, the anchor is assumed to have perfect downward directional stability during its free fall period. The parameters of interest involve sea water density and viscosity variation, which represents the water depth in South China Sea from water surface to a depth of 2000 m as referred to Murray (2004). Besides, the effects of varied design features such as tip angle, aspect ratio, rear angle, and diameter ratio were studied comprehensively in the parametric studies. The values of drag coefficient can be obtained directly from simulation results; while values of terminal velocity has to be found by either manual calculations, or repeating the simulations at various velocities until the resulted drag force equates with the anchor's weight. It is clear that one of the key parameters determining the depth of penetration is the impact velocity, not the terminal velocity. In typical anchoring scenario, the impact velocity will be a fraction of the terminal velocity, depending on the height of release of torpedo anchor. However, it is rather difficult and cumbersome to investigate the impact velocity directly because the range of water depth to be investigated is too wide, ranging from 1000 ~ 3000 m, in addition to too many parameters and unknowns, e.g. angle of impact. An indirect approach is used in this research by observing that under an ideal situation, the impact velocity is proportional to the terminal velocity. Thus, by optimizing the geometric parameters of the torpedo anchor to maximize its terminal velocity, theoretically, it also maximizes the impact velocity of the torpedo.

2.1 Governing Equations

From vertical momentum balance, the reacting force when the anchor is submersed in fluid F_{sub}, minus the drag force F_D, must equal to its acceleration, as follows

$$F_{sub} - F_D = m\frac{dv}{dt} \tag{2}$$

where m is the mass of the torpedo and v is the vertical velocity of the torpedo. The submersible force is given by

$$F_{sub} = mg - \rho_w Vg \tag{3}$$

where ρ_w is the density of seawater, and V is the volume of the torpedo. Once the drag coefficient is calculated from CFD, the drag force can be readily calculated as

$$F_D = \frac{1}{2}\rho_w A_F C_D v^2 \tag{4}$$

where A_F is the frontal area of torpedo calculated using D_2, C_D the drag coefficient, and v is the travelling velocity. Combining Eq. (3) and (4) into (2) yields

$$\left(mg - \rho_w Vg\right) - \frac{1}{2}\rho_w A_F C_D v^2 = m\frac{dv}{dt} \tag{5}$$

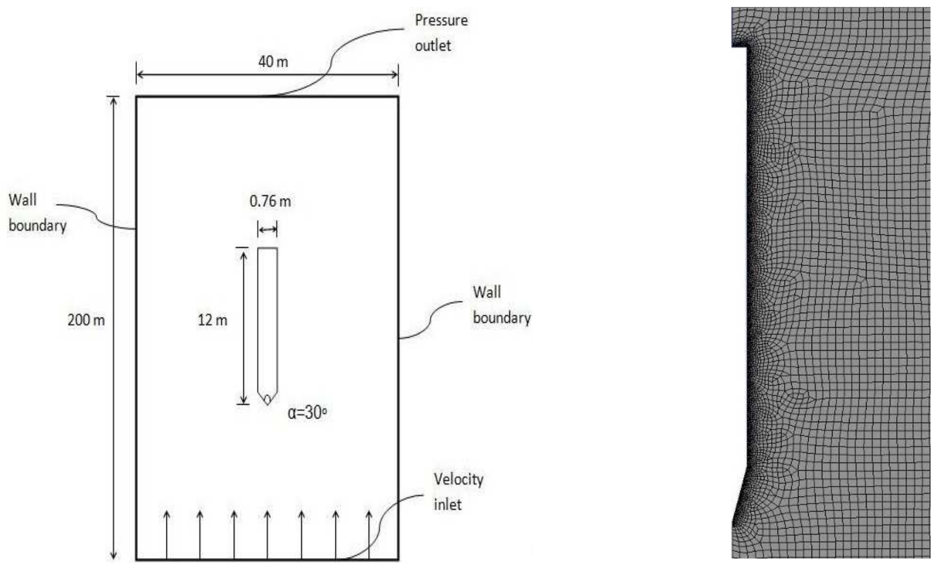
The terminal velocity is achieved when rhs of Eq. (5) equates zero, or

$$v_T = \sqrt{\frac{\left(m - \rho_w V\right)g}{\frac{1}{2}\rho_w C_D A_F}} \tag{6}$$

In the present case, the drag coefficient is obtained from the graph of CFD simulations, while v is taken as the inlet velocity of the simulation model.

2.2 Model development and boundary conditions

The main idea of simulation is that the anchor is set at a stationary position in the middle of the domain with fluid flowing upward through the inlet with pre-defined velocity. The boundary on the anchor surface is assumed no flow boundary. The unsteady simulation was performed using implicit Euler with adaptive time stepping and follows the method described in Raie (2009). Effects of each factor were obtained by repeated simulations with varied values, at recurring different velocities for each set of parameters. The boundaries are designed to be far enough from the torpedo anchor, so that the analyses are not affected by its proximity. Meshing was done with pre-dominantly quadrilateral cells, with small portion of triangular cells for smooth transitions at regions of irregular geometry. The dimensions used as the datum of 2D axisymmetric model is shown in Fig. 1(a). Figure 1(b) show the associated computational axisymmetric model used for the simulation.



(a) (b)

Fig. 1(a) Baseline model with specified dimensions and (b) associated axisymmetric mesh for computation

Besides examining the influences of varied aspect ratio and tip angle for the conventional torpedo anchor design, the effects of newly proposed design features are investigated too, namely rear angle and diameter ratio. Different geometries were created, while the same settings for meshing as well as its solution setup were integrated. Notably, different diameter ratios are achieved by manipulating diameter of the torpedo's lower half body design (D_2).

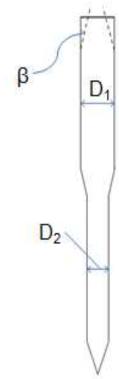


Fig. 2 Illustration of rear angle, β and diameter ratio, D_1/D_2.

In essence, the effects of 6 major parameters were studied. The examined values for the main parameters are presented in Table 2.

Table 2 Parameters for torpedo anchor's simulation

Parameters	**Base Model**	**Present Study**
Anchor weight (kN)	400	400
Diameter, D_1 (m)	0.76	0.5, 0.667, 1.0
Length (m)	12	10
Water density (kg/m^3)	1024	**998.2 – 1027.3**
Viscosity (N.s m^{-2})	0.001005	**0.001 – 0.0015**
Tip angle, α (°)	30	**15, 30, 45, 60**
Aspect ratio (L/D)	15.79	**10, 15, 20**
Rear angle, β(°)	-	**0, 15, 30, 45**
Diameter ratio (D_1/D_2)	1	**1.5, 2.0, 2.5**
Fin	Finless	Finless

2.3 Mesh dependency check

In CFD analysis, this analysis is of utmost importance, as to ensure that number of nodes or cells in the developed model is not affecting the result. In order to achieve that, the mesh was controlled with varying degree of refinement and its sizing. Consequently the resulted drag coefficients were recorded. Simulations were carried out for increasing number of mesh elements. The graph of drag coefficient against number of elements per unit area is plotted in Fig. 3.

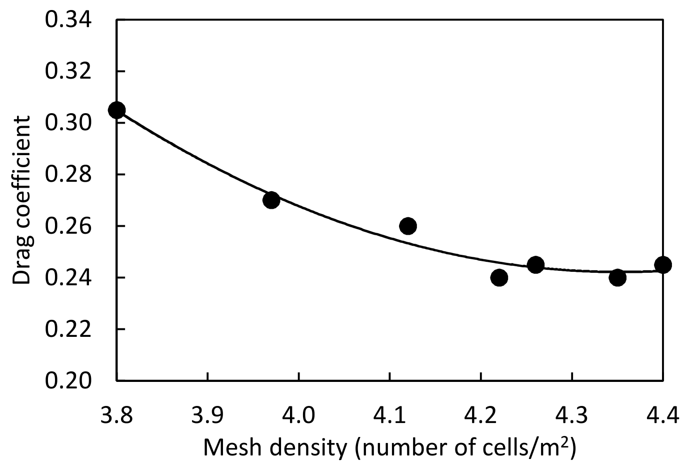


Fig. 3 Drag coefficient versus mesh density (number of cells per unit area).

It is clearly evident that the drag coefficient tends towards a constant when mesh density is increased as depicted in Fig. 3. The final value of drag coefficient is independent of mesh density beyond a certain limit. The coefficient of drag converges from 0.3121 towards stable value of about 0.24 when finer mesh is utilized. Thus, based on Fig. 3, all the simulations henceforth are conducted with mesh density of more than 4.25 cells per unit area and beyond.

2.4 Validation of developed model

Firstly, the developed CFD model was compared with the results published by Raie (2009). In line with the full scale field test performed by Petrobras (Medeiros, 2002), the simulation were done for a T-40 torpedo anchor. It was conducted by using a torpedo anchor made of steel with overall weight of 0.4 MN, length of 12 meters and diameter of 0.76 meters. Consequently, the percentage differences between obtained drag coefficient from CFD simulations and the reported values are 5.58% and 5.73%, for inlet velocity of 80 m/s and 90 m/s respectively. Furthermore, the calculated terminal velocity only deviates 3.76% from the reported value. Both reported values and results from CFD model are tabulated in Table 3.

Table 3 Validation of model with full scale field test as reported by Raie (2009)

Reported result	**CFD prediction**	**% difference**
C_d at 80 m/s : 0.2016	0.2134	5.58%
C_d at 90 m/s : 0.2007	0.2122	5.73%
Terminal velocity, V_T : 87.2 m/s	83.92 m/s (calculated)	3.76%

Another validation was performed by comparison with laboratory test conducted by Hasanloo et al., (2011) as shown in Fig. 4.

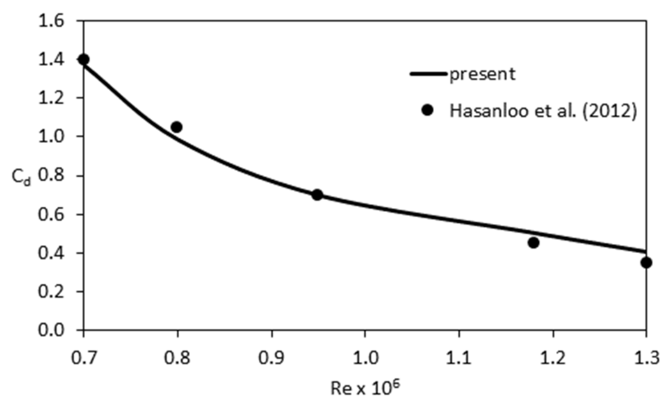


Fig. 4 Comparison of present model with laboratory test of torpedo anchor (Hasanloo et al., 2012).

This validation was conducted according to the specified dimensions. However, it was scaled up 10 times as the prototypes used were 10 times smaller than actual units. The drag coefficients obtained by present model was plotted against Reynolds number. As shown in the Fig. 4, the results acquired from present simulations were very close to the experimental results with an overall error below 5%.

3. RESULTS AND DISCUSSIONS

Comprehensive parametric studies were carried out in this section to investigate the variation of terminal velocity due to tip angle, rear angle, density and viscosity of sea water, diameter ratio and aspect ratio. In any particular section, the values of parameters that remained constant are same as base model listed in Table 2.

3.1 Effects of change of seawater properties

The definition of *deepwater* according to PETRONAS' context are any depth beyond 250 m in the Malay Basin region but below 1500 m in the Northern Borneo water. This definition is shallower than the "deepwater" definition by other companies, e.g. SHELL, but it is a fit-for-purpose definition in the Malaysia's context. Thus, the seawater properties range from 100 – 2000 meters are studied. Figure 5 showed the characteristic curves of drag coefficient versus Reynolds number at varied viscosity. The results are very close to one another, implying that increment in sea water viscosity does not significantly impact the hydrodynamic properties of torpedo anchor. As water viscosity increases, the drag force acting on the anchor changes from 291 kN to 295 kN, a mere 1% increase. In other words, the drag force acting upon the anchor does not vary greatly when water depth varies from 100 – 2000 meters.

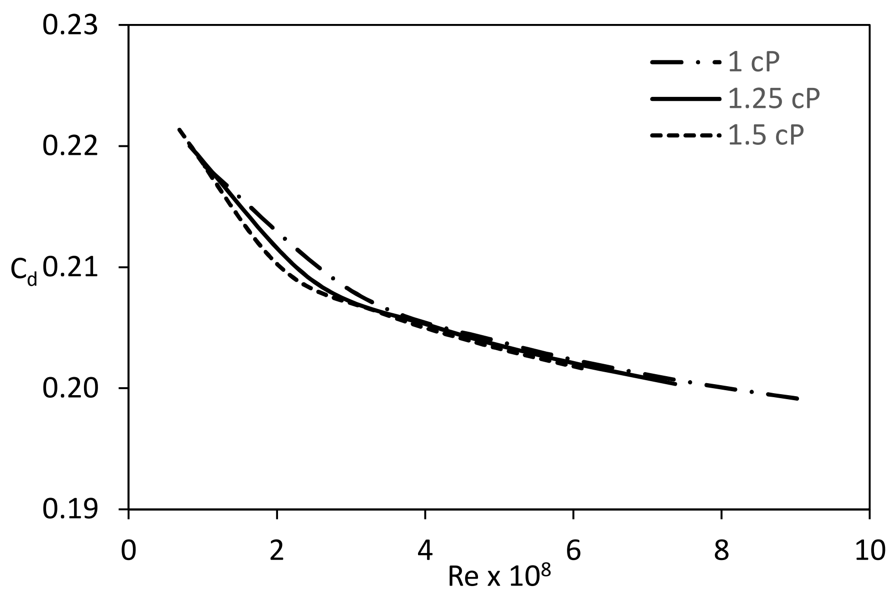


Fig. 5 Characteristic curves of C_d against Re at varied viscosity.

Similarly, the effect of sea water density on the drag coefficient is not significant as shown in Fig. 6. When density increases from 998.3 kg/m^3 (fresh water) to 1027.3 kg/m^3, the resultant drag force changes from 284 kN to 292 kN, a 3% increase. It is thus ascertained that terminal velocity decreases with increasing water depth. However, the increase in upward resisting force is insufficient to be concerned.

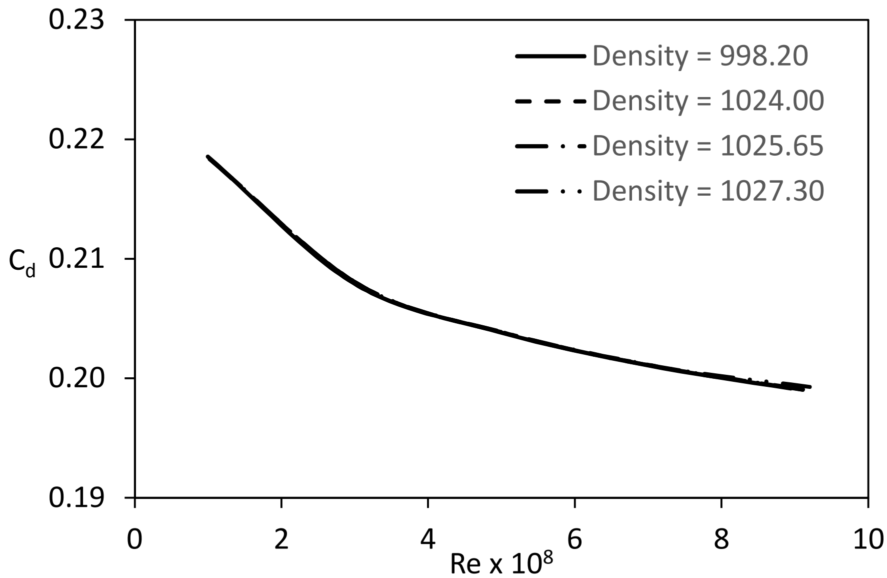


Fig. 6 Characteristic curves of C_d against Re at varied sea water density

3.2 Effects of Tip Angle, α

Figure 7 showed the variation of the torpedo's terminal velocity versus the tip angle. It can be observed that terminal velocity always increases as the tip angle of torpedo anchor decreases. In other words, the drag force acting upon the anchor increases as the anchor's tip become wider. As the graphs for different viscosity almost overlaps for the same density, verifying again that the viscosity of sea water plays trivial role in altering the torpedo's hydrodynamics.

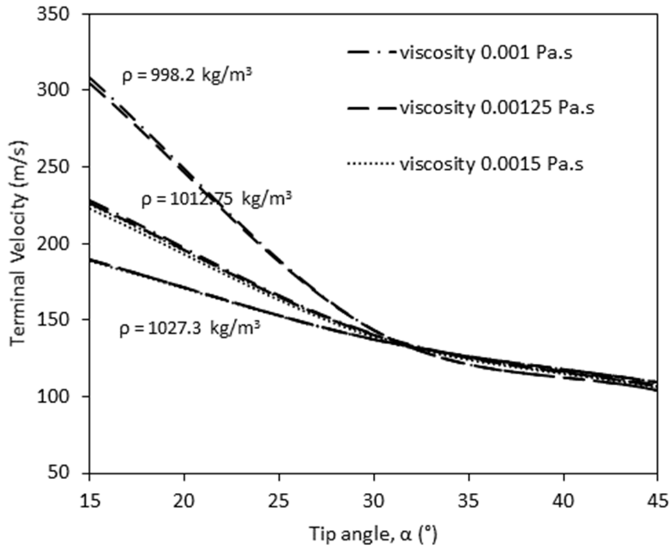


Fig. 7 Effects of tip angle on terminal velocity at varied sea water density and viscosity.

Figure 7 indicates that in order to improve the anchor's terminal velocity significantly, a 15^o tip angle can be implemented in its design. It is notable that there is an inflexion point for all studied conditions, which is at tip angle of 30^o. Beyond 30^o, the effect of tip angle on the terminal velocity becomes less significant, as it can be seen the graph gradient became much smaller. Furthermore, as it can be observed from the graph gradient of different water density, the influence of tip angle becomes more dominant as density is lower. In other words, with the aim of achieving higher terminal velocity, the significance of altering tip angle is greater in shallower sea region as compared to deep sea region. In essence, in order to ensure higher terminal velocity, an optimum tip angle of 30^o or smaller should be utilized.

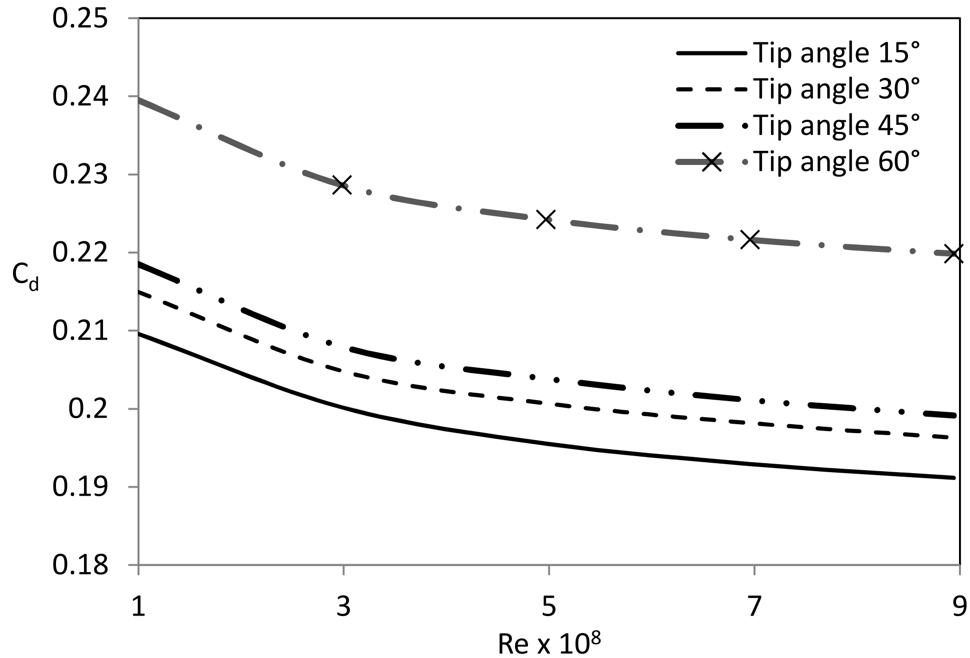


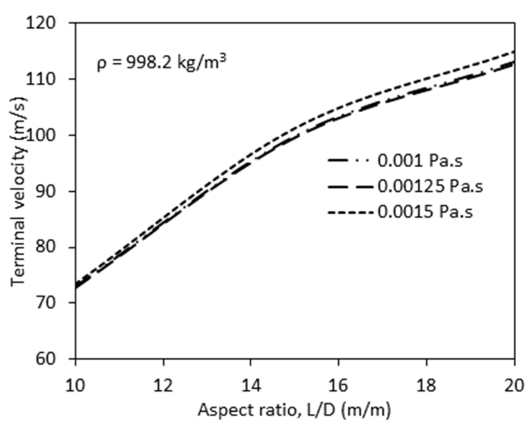
Fig. 8 Drag coefficient versus Reynolds number for different tip angles

Figure 8 depicted the drag coefficient versus the Reynolds number for different tip angles, varied from 15° to 60°. As a result, tip angle of 60° has notably highest drag coefficient as compared to lower tip angles of 15°, 30°, and 45° respectively. As tip angle varies from 15° to 45°, drag force acting on the anchor increases steadily from 270.09 kN to 281.36 kN. Thereafter, more drastic changes in the resisting force can be observed as tip angle increase. Consequently, the anchor's terminal velocity decreases as tip angle increases from 15° to 60°. Thus, a design of torpedo anchor with tip angle beyond 45° is to be avoided. Sharper anchor tip would allow the torpedo to gain higher vertical downward speed with reduced drag coefficient.

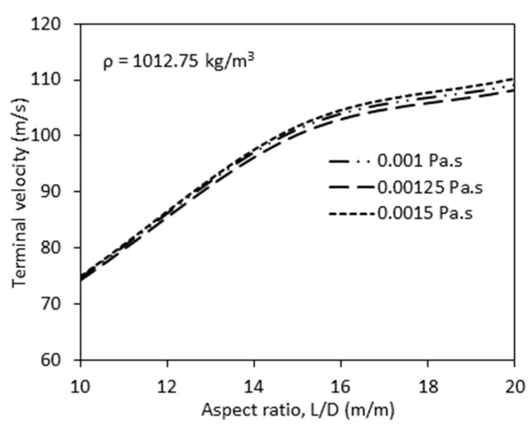
3.3 Effects of Aspect Ratio (L/D)

The aspect ratio was varied by changing the overall diameter of the torpedo anchor design. Aspect ratio of 10, 15, and 20 requires overall diameter to be 1.0, 0.667, and 0.5 meters respectively. As it can be observed from Fig. 9(a), 9(b), and 9(c), terminal velocity increases when aspect ratio of torpedo anchor is increased. In all conditions, the variation in terminal velocity due to changes in aspect ratio is greater, with resulted values ranged between 75 m/s to 115 m/s. Terminal velocity is notably more sensitive towards changes in aspect ratio compared to variation in tip angle. This is because the drag force is basically a function of contact area between surrounding fluid and the whole submerged surface area of torpedo. Thus, the aspect ratio plays a dominant effect than the tip angle. In all cases shown in Fig. 9, there exists an inflection point at which the aspect ratio becomes less influential, that is after an aspect ratio of 15. Besides, changes in aspect ratio will have greater influence on the terminal velocity in shallow water in comparison to deeper water. In conclusion, anchor's terminal velocity approaches a threshold value when the aspect ratio approaches 15; and the effect is even prominent in deeper sea region.

Smaller aspect ratio has notably much higher drag coefficient, as it is illustrated in Figure 10. Consequently, the terminal velocity can be increased with higher aspect ratio as the drag force is lowered. When aspect ratio is adjusted, drag force varied from 117.84 kN to 1026.97 kN. In addition, it is noteworthy to realize that the resulted drag force is reduced towards consistent value, beyond the point at which aspect ratio is 15.



(a)



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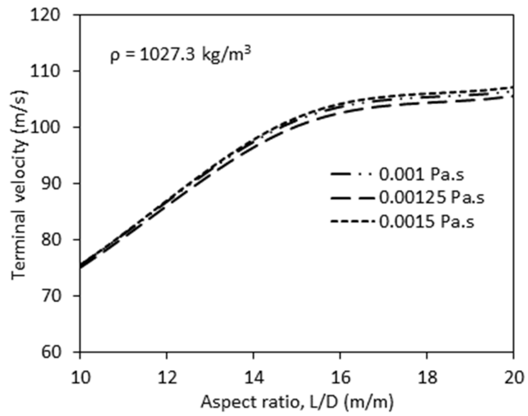

(c)

Fig. 9 Effects of aspect ratio on terminal velocity with different viscosities at sea water density of (a) 998.2 kg/m^3, (b) 1012.75 kg/m^3 and (c) 1027.3 kg/m^3

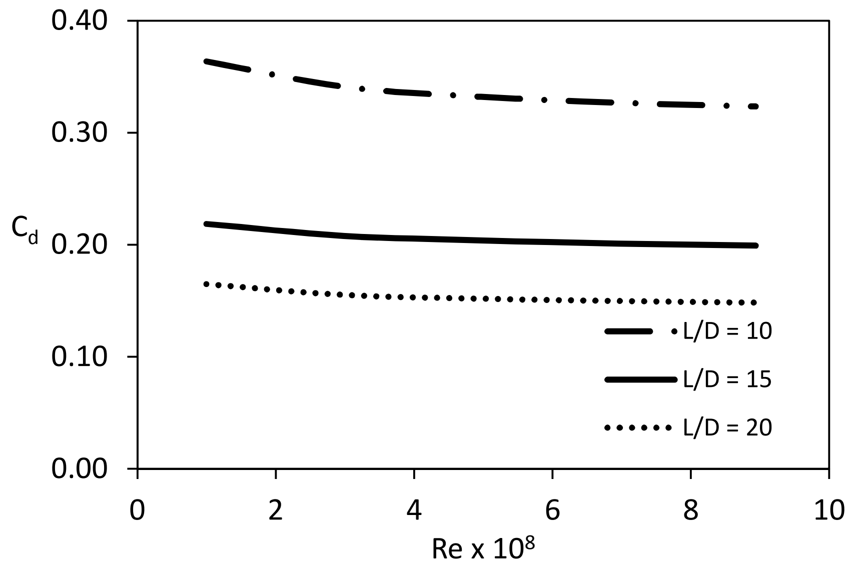

Fig. 10 Drag coefficient versus Reynolds number at different aspect ratios.

3.4 Effects of Rear Angle, β

Figure 11 showed the effects of rear angle on terminal velocity for different densities and viscosities. It is obvious that in shallow water, terminal velocity reaches its optimum values at rear angle of 30^o. The decrease in terminal velocity thereafter can be due to the vortices of fluid flow at the end of torpedo anchor, when the rear part becomes too sharp. This may also be resulted due to the presence of reversed flow, when rear angle is designed to be greater than 30^o. However, for deeper sea water with higher density, the terminal velocity still does increase with rear angle greater than 30^o, instead of decreasing beyond that point. Thus, this finding should be taken into consideration for the anchorage systems of floating platforms at different depth. The implementation of new design feature: rear angle, turned out to be capable of improving the hydrodynamics of torpedo anchor. By way of introducing an angle at the end of torpedo anchor design, the drag force will be reduced as compared to the original design. Subsequently, the greater downward acceleration is allowed to achieve higher terminal velocity. The drag coefficient varies from 0.2096 to as low as 0.0905 as rear angle is introduced. Nevertheless, there is an optimum rear angle at 30^o, which results in lowest drag coefficient and therefore smallest drag force. The re-bounce of drag acting upon the anchor might be due to reversed flow or vortices of fluid at rear end of torpedo anchor. Anyhow, the inclusion of rear angle in torpedo anchor design is beneficial for its hydrodynamics.

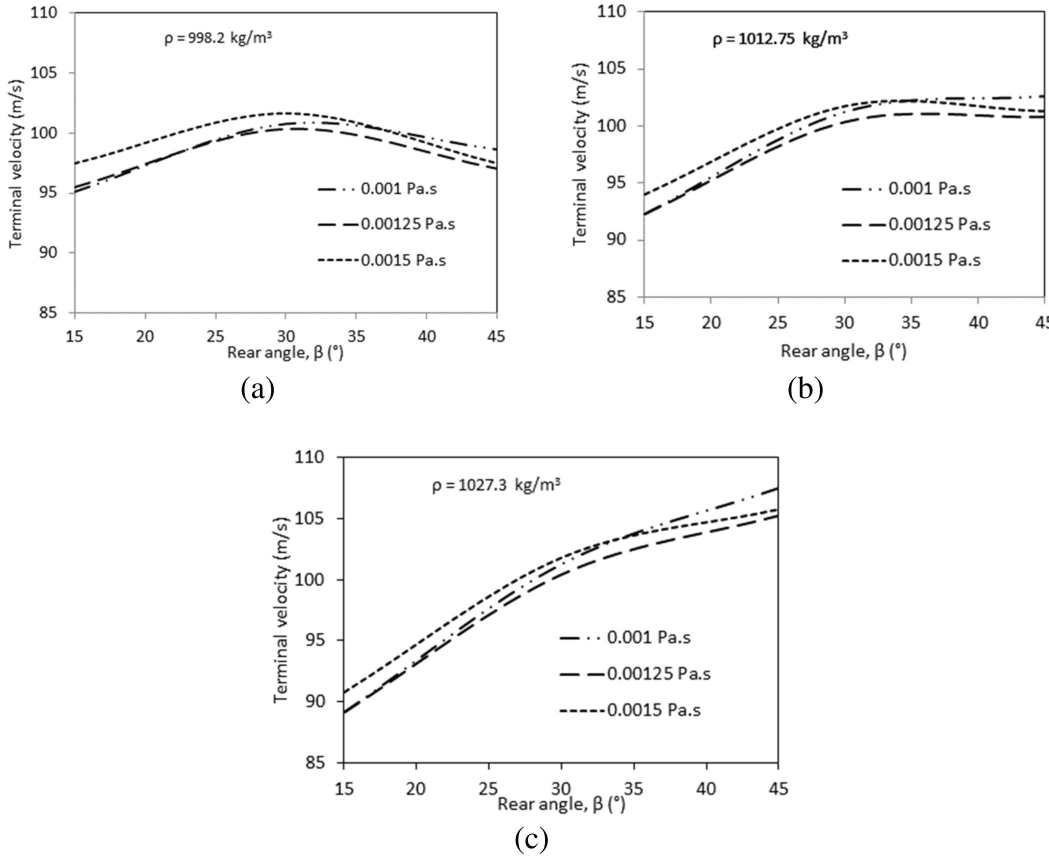

Fig. 11 Effects of rear angle on terminal velocity with different viscosities at sea water density of (a) 998.2 kg/m^3, (b) 1012.75 kg/m^3, and (c) 1027.3 kg/m^3.

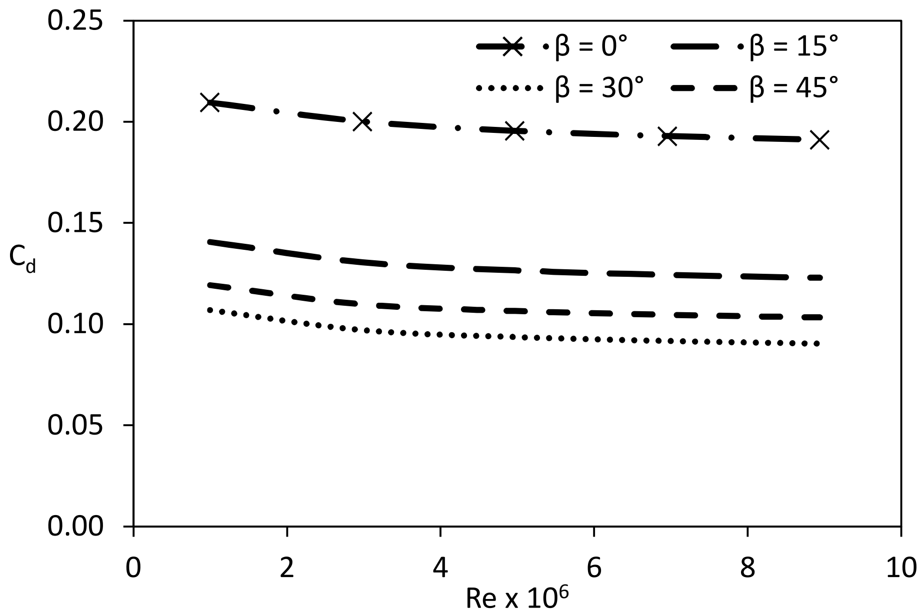

Fig. 12 Characteristic curves of drag coefficient against Reynolds number at various rear angles

3.5 Effects of Diameter Ratio (D_1/D_2)

Figure 13 showed the effect of diameter ratio on terminal velocity at different sea water densities and viscosities. As it can be seen, terminal velocity increases with greater diameter ratio. In other terms, smaller diameter for the lower half of torpedo anchor design is beneficial for reducing drag as compared to the industrial design. Based on Fig. 13, it is verified that implementation of diameter ratio in the designs of torpedo anchor can improve its terminal velocity. However, the gradient in Figure 13(a), (b), and (c) become steeper when diameter ratio is greater than 2. This signifies that when designing the anchor, diameter ratio of greater than 2 would result in greater improvements in its aerodynamics. Besides, the execution of diameter ratio is more beneficial when viscosity of the sea water is at lower values. On the other hand, Figure 14 showed the graph of drag coefficient versus Reynolds number for different diameter ratios. When the diameter ratio is increased up to 2.5 from the original design, small variation in drag coefficient is observed, from 0.2041 to 0.206. There is a discrepancy in the obtained drag force, at which the reducing drag force rises again when diameter ratio varies from 1.5 to 2.0. Overall, the drag coefficient curves for different diameter ratios are in proximity with one another. In other words, diameter ratio is not significantly effective in improving the aerodynamic characteristics of torpedo anchor. However, this design feature will result in lower amount of materials used, and therefore reducing the cost. This cost reduction can be substantial as the cost of steel and aluminum often fluctuate at around 600 USD and 1200 USD per ton.

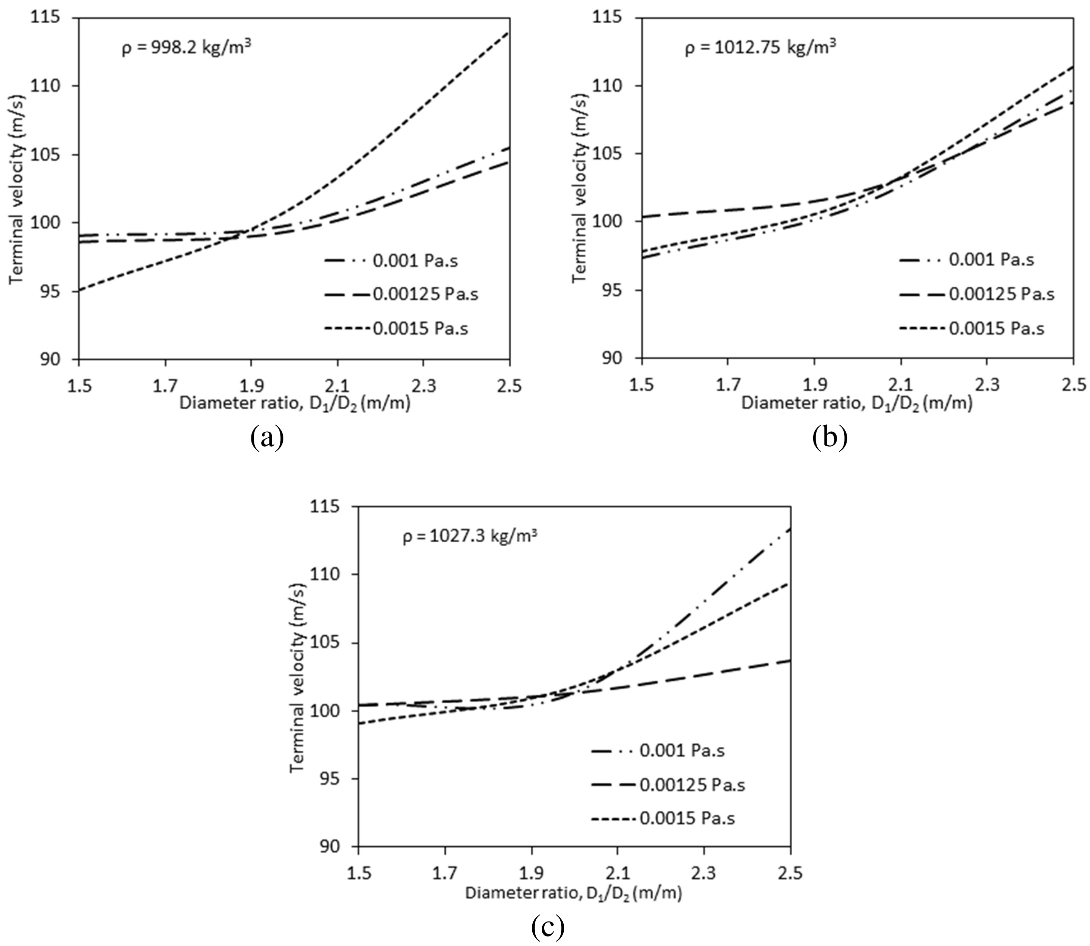

Fig. 13 Effects of diameter ratio on terminal velocity with different viscosities at water density of (a) 998.2 kg/m^3, (b) 1012.75 kg/m^3, and (c) 1027.3 kg/m^3.

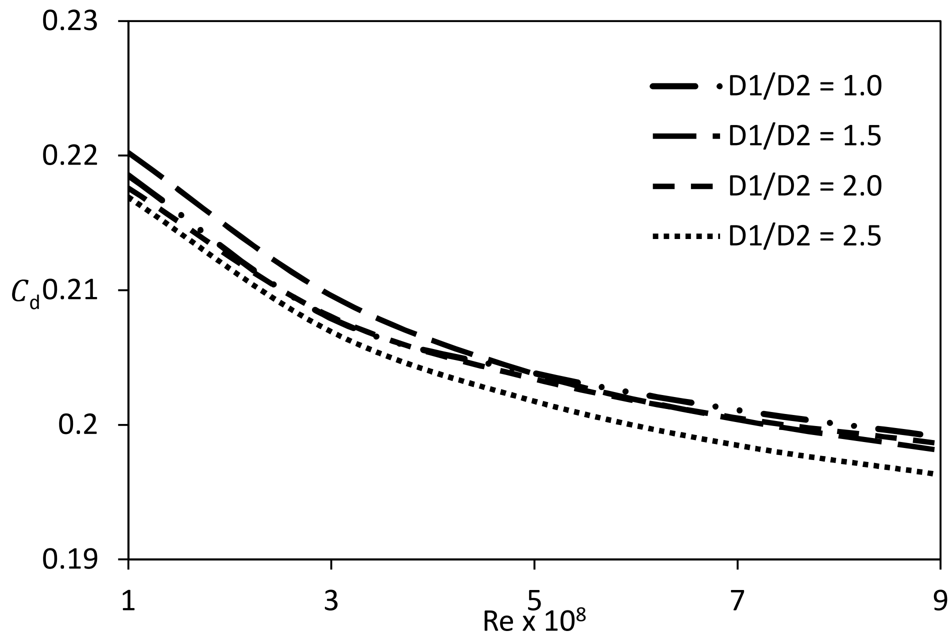

Fig. 14 Drag coefficient versus Reynolds number for different diameter ratios.

3.6 Effect of tip shape

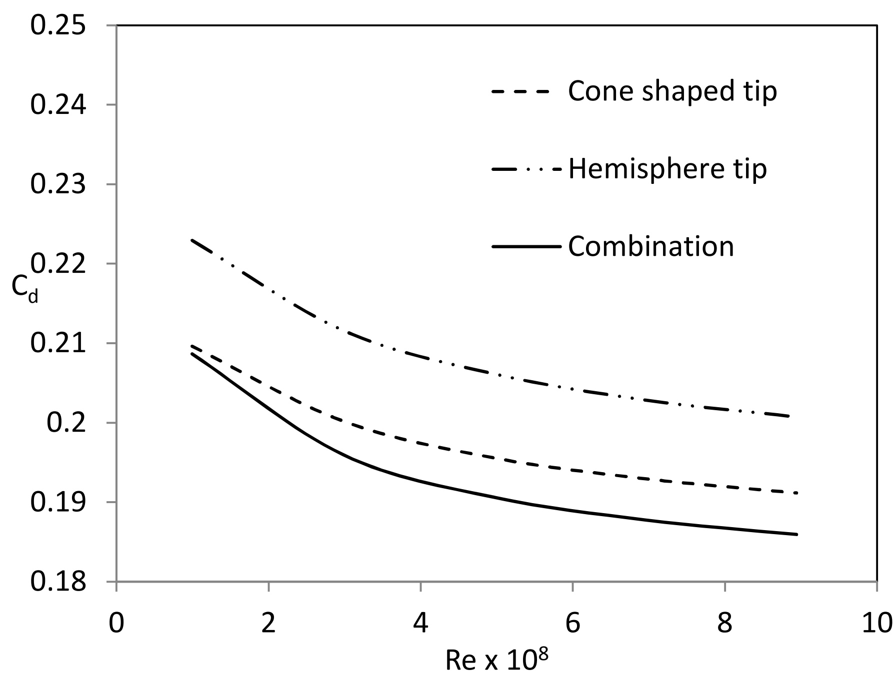

Fig. 15 Characteristic curves of C_d against Re for different tip shape

The effects of different shape of anchor's tip were also studied. Simulations were conducted for tip shapes of cone, hemisphere, and a combination of these two, as shown in Figure 15. A design of anchor tip with combination of cone and hemisphere shape will result in the lowest drag coefficients. However, the different tip shape was not included in the overall sensitivity analyses due to the fact that the effect of tip angles has been studied.

3.7 Sensitivity Analysis

Figure 16 showed the sensitivity of drag coefficients with respect to different parameters, with values ranged according to Table 2. As a result, it showed that aspect ratio is the most influential factor that can be used to manipulate the drag coefficient effectively. This conclusion is not dissimilar to the results reached by Hasanloo and Yu (2011). This is followed by the rear angle, water viscosity, water density, anchor's diameter ratio, and lastly tip angle being the least dominant factor.

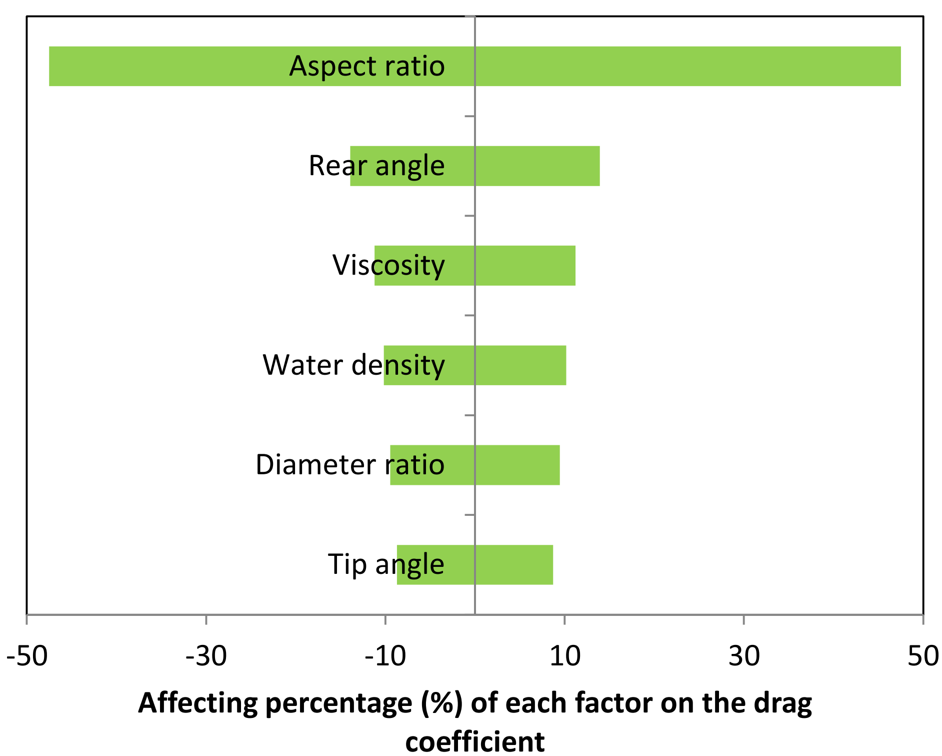

Fig. 16 Affecting percentage of each studied parameters towards the drag coefficient.

4 CONCLUSION AND RECOMMENDATION

It is known that the anchor will have to encounter higher drag force to achieve greater terminal velocity as the water depth increases. However, the effect of water depth is not significant for torpedo anchor, as its terminal velocity does not vary much with increased sea water density and viscosity. Besides, higher terminal velocity can be achieved by implementing greater aspect ratio, lower tip angle, greater β, and greater diameter ratio into its design. It is noteworthy to recognize the optimum tip angle is 30^{o} and below. In line with that, the effect of diameter ratio is not substantial, but it may be utilized as one of the cost and material reduction measure. Drag coefficient is most sensitive towards changes in aspect ratio, and its influence can be as high as 47% quantitatively in comparison to any other parameters. It can be concluded that aspect ratio is the most dominant factor in determining the hydrodynamic properties of torpedo anchors. Lastly, both of the proposed design features, rear angle and diameter ratio greater than 1 are capable of reducing the drag acting upon the anchor for better installation. Further research can be extended to study the degree of tilt when the anchors is free falling, in order to ensure better directional stability for effective penetration. Moreover, the effective holding capacities of different anchor design should be examined, as this would be very useful for applications by the industry. The important factors which affect the anchors' holding capacity should be identified and further improved. In line with that, feasibility studies can be done for usage of torpedo anchor, by studying the variation in soil properties in different sea regions.

NOMENCLATURE

A	Boundary area, [m^2]
α	Tip angle, [-]
β	Rear angle, [-]
C_d	Drag coefficient

D	Overall diameter, [m]
D_1/D_2	Diameter ratio, [-]
L	Overall length [m]
L/D	Aspect ratio, [m/m]
$\hat{\mathbf{n}}$	Outward unit normal, [-]
Re	Reynolds number, [-]
t	Time, [s]
$\mathbf{u}$	Velocity vector, [m/s]
v	Vertical velocity, [m/s]
v_T	Terminal velocity, [m/s]
$\mathbf{V}$	Volume [m^3]
ρ	Fluid density, [kg/m^3]
μ	Water viscosity, [N.s/m^2]

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