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Numerical Study of Kaplan Series Propeller using CFD: Effect of Angle of Attack and Number of Blade Variations

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ABSTRACT

Kaplan series propeller has the potential to improve ensuring the high ship propulsion performance of the operation. In this study, a Kaplan propeller is evaluated with a Controllable Pitch Propeller (CPP) behavior such as angle of attack and the number of blades. The propeller blades which are studied are 3, 4, and 5 blades with the angle of attack about 10.3°, 15.3°, and 20.0°. The method in this study is using Computational Fluid Dynamic (CFD) simulations. Moreover, surface pressure, thrust, torque, and efficiency are evaluated due to the influence of the angle of attack variations. It has been found that varying the angle of attack significantly affects the distribution of the pressure surface of the propeller. The pressure gradually increases at the higher level of the angle of attack. Furthermore, it is well known that variations in the angle of attack and the number of blades significantly affect propeller performance as expressed by propeller thrust and torque values. Thrust and efficiency tend to increase at higher levels of the angle of attack. However, it tends to decrease at the propeller with more blades on it.

1. Introduction

The propeller is a very important part that determines the maneuverability of the ship. The propeller itself is defined as a tool that is used to generate thrust derived from the engine power that's transmitted thru the shaft. In other words, the propeller functions to convert engine power into thrust according to the combination of rotation per minute (RPM) and speed. A propeller is a machine component that converts rotational motion into thrust by transmitting force. A pressure ratio is created between the front and back surfaces of the blade.

The development of the propeller blade design is getting better with an adequate aerodynamic shape so that it can produce more thrust significantly. For ship propulsion system, propeller blade has a lot of types [1-3]. Based on the mechanism of the propeller blade holder system, there are two types of mechanisms that are commonly used that is fixed mechanism namely a Fixed Pitch Propeller (FPP), and a mechanism with an adjustable angle of attack which is commonly namely a Controllable Pitch Propeller (CPP) or Variable Pitch Propellers (VPP). Based on the performance and efficiency of

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the simple propeller shape, it was turned into a B-Screw propeller mainly used for propulsion systems on merchant ships [4,5]. However, the CPP mechanism is more profitable than the FPP mechanism because the CPP can generate varying thrust with constant propeller rotation.

Over the past decades, extensive studies have been conducted using computational fluid dynamics (CFD). Hang *et al.,* [6] measured the performance of the propeller using CFD to predict the aerodynamic characteristics at different propeller disc angles, aerodynamic coefficients of NACA 0012 Airfoil by Abobaker *et al.,* [7], and the aerodynamic performance of hatchback considering the effect of the yaw angle by Cheng *et al.,* [8]. Jaafar *et al.,* [9] modified the trailing edge design to evaluate the impact on the performance of wind turbine airfoils. It shows that the lift coefficient increases due to the angle of the inclined trailing edge. Evaluation of the performance of wind turbines due to the inflow parameters in an atmospheric boundary layer has been conducted by Bahambary *et al.,* [10]. The results show that in the all-around inflow profile, the power law profile is better.

In the marine field, CFD is generally used to simulate the performance of the propeller. Permadi *et al.,* [11] investigate the performance of B-series propeller models using a multi-reference frame (MRF) approach to select the optimal B-series propeller design. Arifin *et al.,* [12] identified the flow separation evaluation of tubercle ship propellers. The results show that the shape of the tubercle propeller has a critical effect on the performance of the propeller when the total pressure of the propeller blade flows over a reduced surface, especially at the edge. Yusvika *et.al.,* [13] predicted cavitation in marine propellers based on temperature and fluid properties and the results show that the cavitation trend is more aggressive at high water temperatures than at low temperatures. Another study was conducted on a CFD approach to propeller cavitation by Mohammad Danil *et al.,* [14] and Zheng *et al.,* [15], and the CFD approach to the performance of propeller was investigated in the previous research by Arifin *et al.,* [16], and Lovibond *et al.,* [17].

Since there is a limited study that focused on the Ka-Series propeller [18,19]. In this study, CFD simulation is conducted to analyze the effect of the angle of attack and the number of blade variations on the performance of the Kaplan-Series (Ka-Series) propeller. The simulation is performed to blade number Z=3 (Ka-3), Z=4 (Ka-4), and Z=5 (Ka-5) to analyze the influence of the different number of the blade with the angle of attack (ϴ) variation ϴ = 10.3^o, ϴ = 15.3^o, and ϴ = 20.0^o. The pressure, force, and thrust of the propeller are identified and the simulation results are compared, then the efficiency of the propeller is discussed. It is believed that as the angle of attack increases, the drag also increased. It means it can affect the performance of the propeller [20].

2. Methodology

Kaplan-Series propellers are used for simulation. This study aimed to confirm the impact of the ϴ and the number of propeller variations on the performance of Ka-Series propellers. The efficiency of the Ka-Series propeller is expressed by the distribution of pressure (Pa), thrust (N), and torque (Nm). However, ship propeller has their characteristic and different performance curves. Thus, the propeller characteristics can be displayed in a diagram function that consists of the coefficient of thrust (KT) with Eq. (1), coefficient of torque (KQ) with Eq. (2), and coefficient of advanced speed (J) with Eq. (3) [21-23]. The calculation of KT and KQ is on an equation in which T_{prop} is the thrust propeller, Q_{prop} is defined as the torque propeller, the fluid density with ρ, the diameter of the propeller or D, n is rotational speed, η_0 is propeller efficiency (Eq. (4)), and Va is advanced speed.

$$\mathrm{KT} = \frac{\mathrm{T_{prop}}}{\rho \times \mathrm{n}^2 \times \mathrm{D}^4} \tag{1}$$

$$KQ = \frac{Q_{prop}}{\rho \times n^2 \times D^4} \quad (2)$$

$$J = \frac{Va}{n \times KQ} \quad (3)$$

$$\eta_0 = \frac{J \times KT}{2\pi \times KQ} \quad (4)$$

2.1 Propeller Design

The simulation is carried out on a Ka-Series propeller with blade number Z=3 (Ka-3), Z=4 (Ka-4), and Z=5 (Ka-5), and with the angle of attack variation $\Theta = 10.3^o$, $\Theta = 15.3^o$, and $\Theta = 20.0^o$. The Θ is calculated by configuring the $P/D_{07} = 0.4$, $P/D_{07} = 0.6$, and $P/D_{07} = 0.8$ according to the following equation Eq. (5) and Eq. (6). Moreover, the detail of the calculation of Θ is shown in Table 1.

$$\Theta = \tan^{-1} \frac{P/D_{0.7}}{2\pi R_{0.7} D} \quad (5)$$

$$\Theta = \tan^{-1} \frac{P/D_{0.7}}{0.7\pi} \quad (6)$$

Table 1
Configuration of Θ

D	$P/D_{0.7}$	$(P/D_{0.7})/(0.7R)$	θ(rad)	θ(degree)
30	0.4	0.18189	0.1799	10.3
	0.6	0.27284	0.2664	15.3
	0.8	0.36378	0.3489	20.0

The developed propeller design in this study is Ka-3, Ka-4, and Ka-5 with a diameter is 30, and the variation of the angle of attack is 10.3^o, 15.3^o, and 20.0^o. As the first stage, the design of the Ka-Series propeller model in this study was created by plotting the propeller coordinate. The coordinates point of the propeller model is shown in Table 2 to Table 4 with Figure 1 as the visualization example.

Table 2
Ordinate of Ka-3 propeller

r/R	Centerline to Trailing Edge D30	Centerline to Leading Edge D30
0.2	3.03	1.69
0.3	3.11	2.11
0.4	3.09	2.65
0.5	3.17	3.06
0.6	3.34	3.33
0.7	3.52	3.52
0.8	3.65	3.65
0.9	3.78	3.78
1	3.80	3.80

Table 3
Ordinate of Ka-4 propeller

r/R	Centerline to Trailing Edge D30	Centerline to Leading Edge D30
0.2	2.21	1.22
0.3	2.30	1.54
0.4	2.29	1.96
0.5	2.36	2.27
0.6	2.48	2.48
0.7	2.62	2.62
0.8	2.73	2.72
0.9	2.82	2.82
1	2.84	2.84

Table 4
Ordinate of Ka-5 propeller

r/R	Centerline to Trailing Edge D30	Centerline to Leading Edge D30
0.2	1.75	0.95
0.3	1.83	1.22
0.4	1.83	1.56
0.5	1.88	1.81
0.6	1.98	1.98
0.7	2.09	2.09
0.8	2.18	2.18
0.9	2.26	2.26
1	2.27	2.27

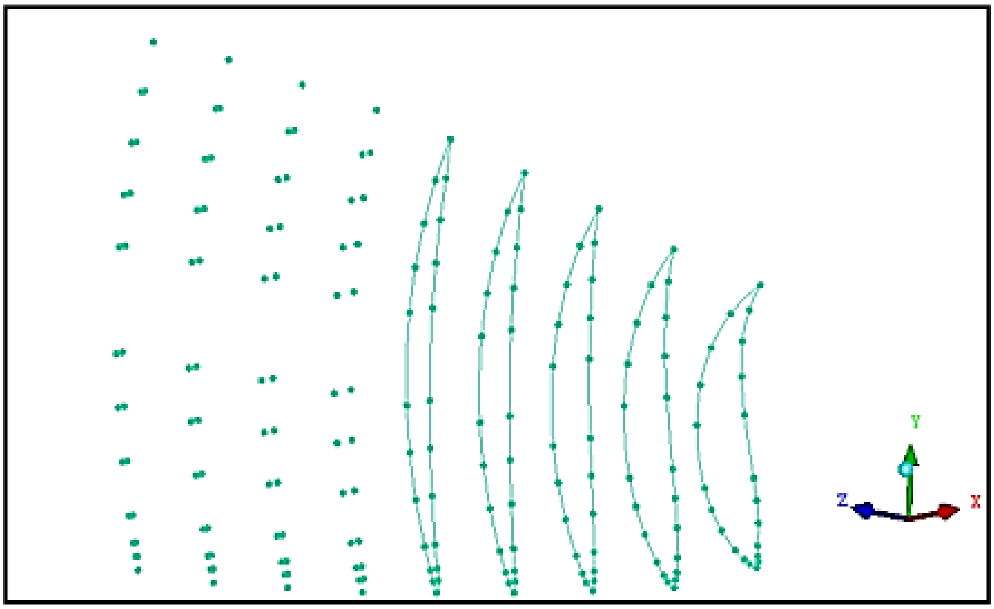


Fig. 1. Propeller coordinates point

The configuration of the propeller model to be simulated using CFD are consisting of 9 models i.e., 3 models for Ka-3, 3 models for Ka-4, and 3 models for Ka-5. The configuration and the propeller geometry of Ka-3, Ka-4, and Ka-5 are expressed in Figure 2.

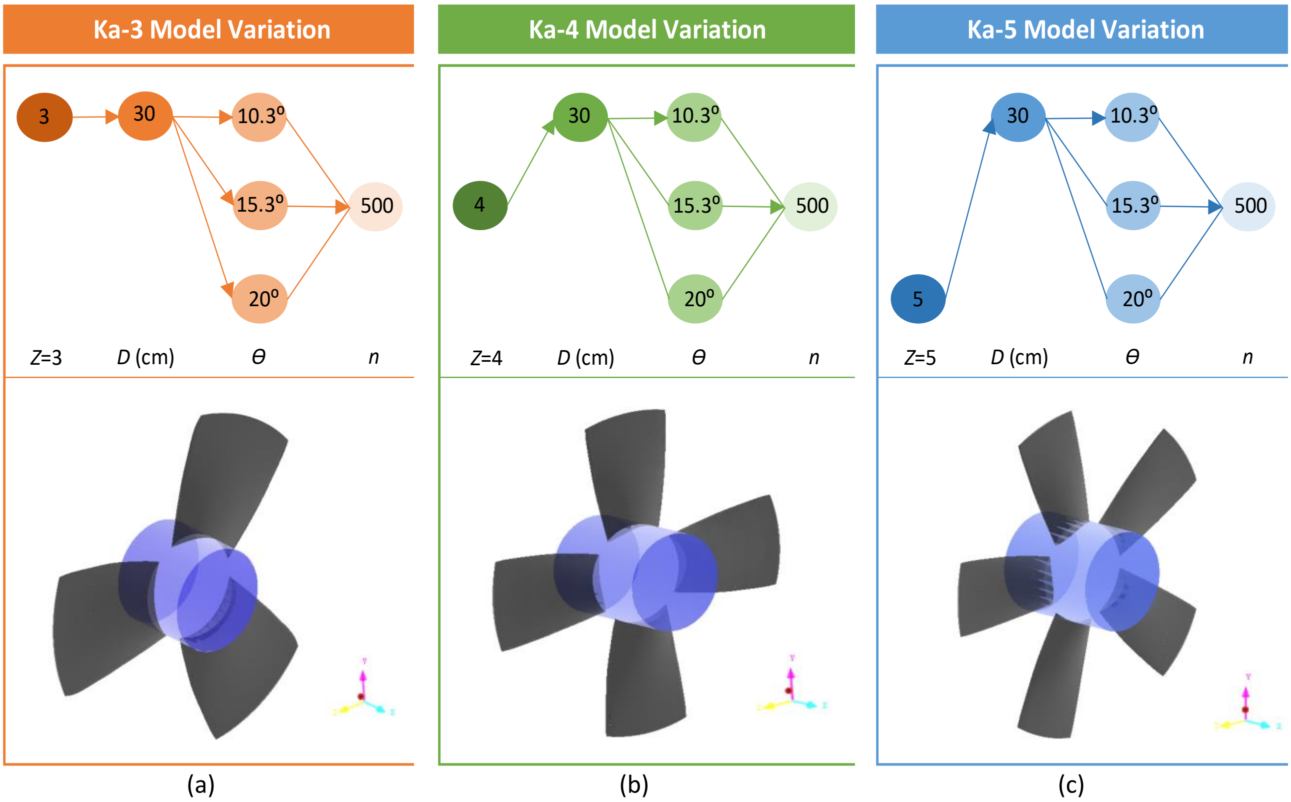


Fig. 2. (a) Propeller model variation of 3 blades (Ka-3) (b) Propeller model variation of 4 blades (Ka-4) (c) Propeller model variation of 5 blades (Ka-5)

2.2 Numerical Study

The geometry of the Ka-series was created using the propeller ordinate. CFD software is used to numerically determine torque and thrust values for each optimal propeller characteristic. The simulations in this study are conducted in an open water environment where two boundaries are developed in the CFD simulations: an outer boundary and an inner boundary [24-26]. The outer boundary is defined as a fixed boundary and the inner boundary is defined as a rotational/rotating boundary. The propeller position is set on the 2/3 outer boundary length from the inflow side. To solve the governing equation with coarse mesh type in the simulation, the multiple reference frame (MRF) is used. The computational boundary setup of unstructured mesh is shown in Figure 3.

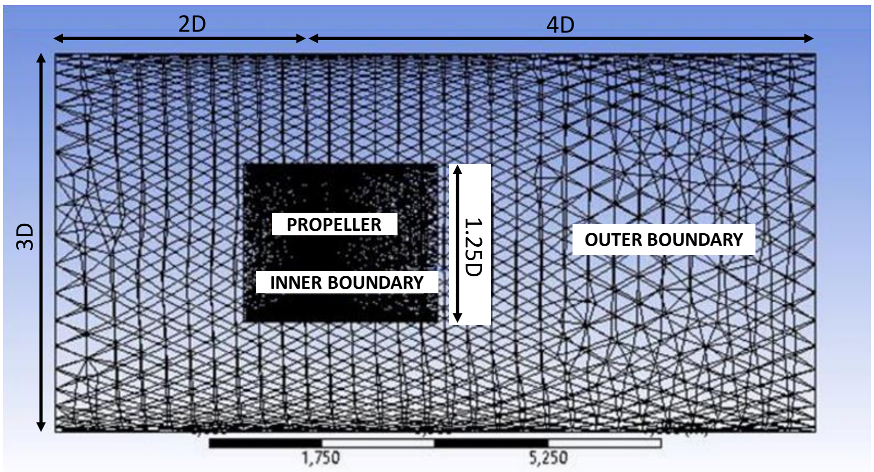


Fig. 3. Configuration of boundaries setup for open water simulation

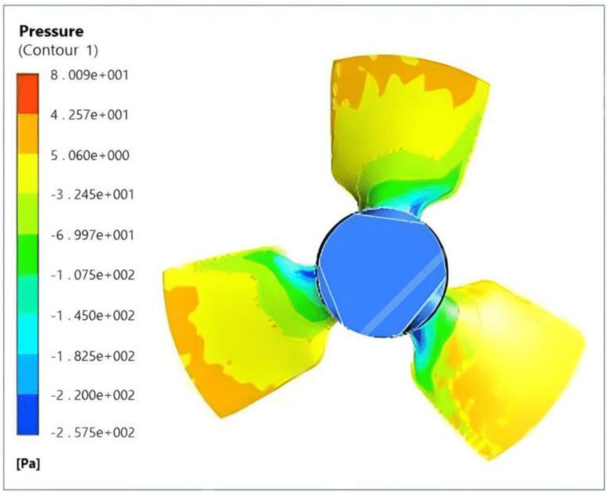
3. Results

In this section, the performance of the Ka series CPP is discussed by investigating the influence of changing the angle of attack and the number of propellers. This study discusses the propeller pressure surface response, thrust, torque, and efficiency.

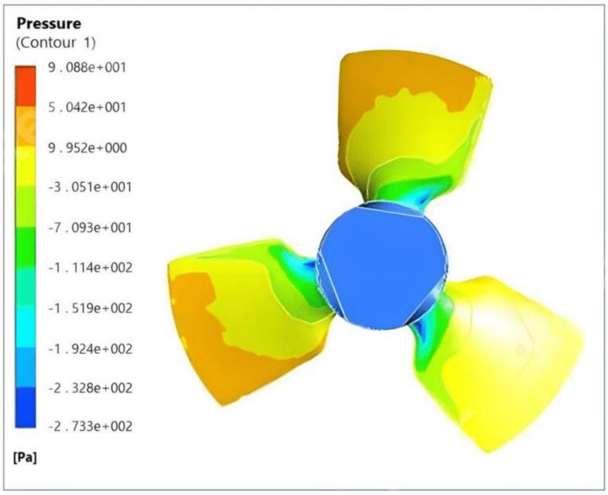
3.1 Characteristics of Pressure Surface

The pressure surface distribution comparison between the face and back side of the propellers model are expressed in Figure 4 to Figure 5 for Ka-Z3: (a) for ϴ = 10.3^o, (b) for ϴ = 15.3^o, and (c) for ϴ = 20.0^o; Figure 6 to Figure 7 for Ka-Z4: ϴ = 10.3^o, (b) for ϴ = 15.3^o, and (c) for ϴ = 20.0^o; and Figure 8 to Figure 9 for Ka-Z5: for ϴ = 10.3^o, (b) for ϴ = 15.3^o, and (c) for ϴ = 20.0^o respectively. In the pressure distribution figures of the propeller, it can be observed that the pressure distribution on the face section is lower compared to the back section. This is reasonable because high pressure is generated on the back section which causes high torque and thrust. Additionally, increasing the angle of attack results in higher pressure on both the face and back sides. This is possible because increasing the angle of attack leads to a higher pitch of the propeller, which in turn produces higher thrust and torque, affecting the pressure distribution on the propeller surface.

Based on Figure 4(a), Figure 4(b), Figure 4(c), Figure 5(a), Figure 5(b), Figure 5(c) Figure 6(a), Figure 6(b), Figure 6(c), Figure7(a), Figure 7(b), Figure 7(c), Figure 8(a), Figure 8(b), Figure 8(c), Figure 9(a), Figure 9(b), and Figure 9(c), it can be seen that the high pressure was also more distributed in the propeller back side of model Ka-Z4 with ϴ = 20.0^o and Ka-Z5 with ϴ = 20.0^o respectively, compared to the other model's variations. However, the Ka-Z4 propeller with four blades exhibits a smaller pressure distribution on certain angles of attack. This may be due to the propeller's efficiency, which is also influenced by the flow rate towards the propeller, depending on the ship's speed. Nonetheless, further identification is required on the pressure distribution as it undoubtedly affects the propeller's performance, such as thrust, torque, and efficiency.



(a)



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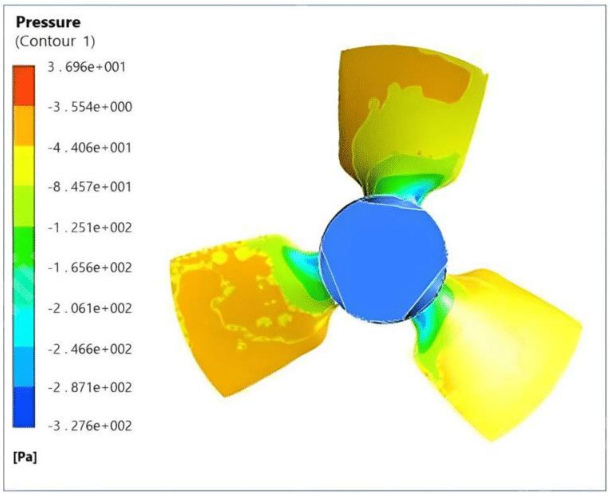
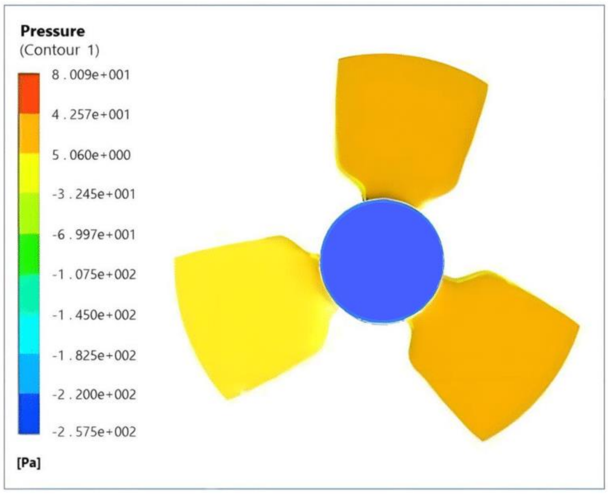
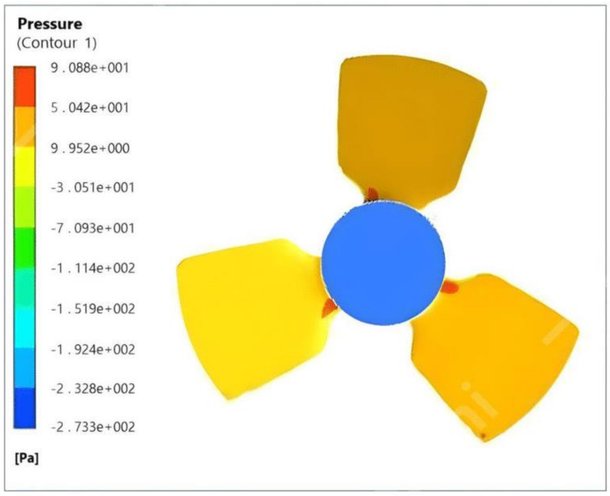


(c)

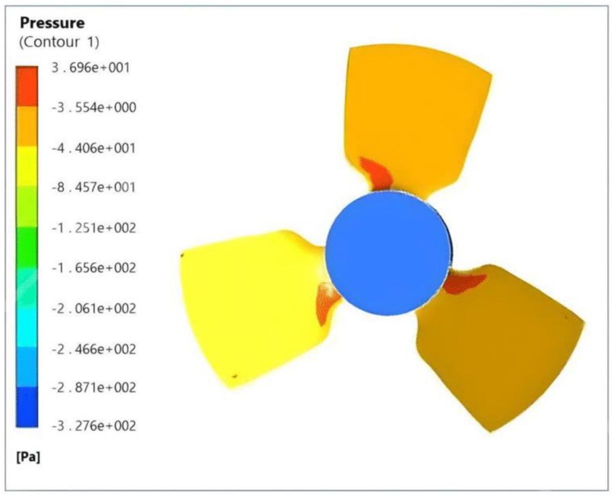
Fig. 4. Distribution of face surface pressure of Ka-Z3 (a) ϴ = 10.3^o (b) ϴ = 15.3^o (c) for ϴ = 20.0^o



(a)

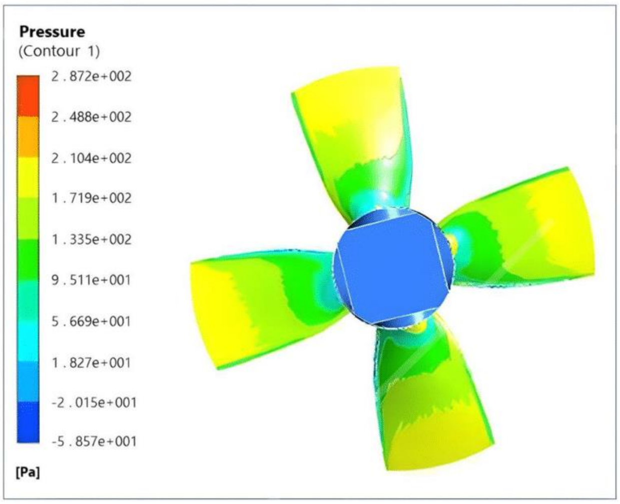


(b)

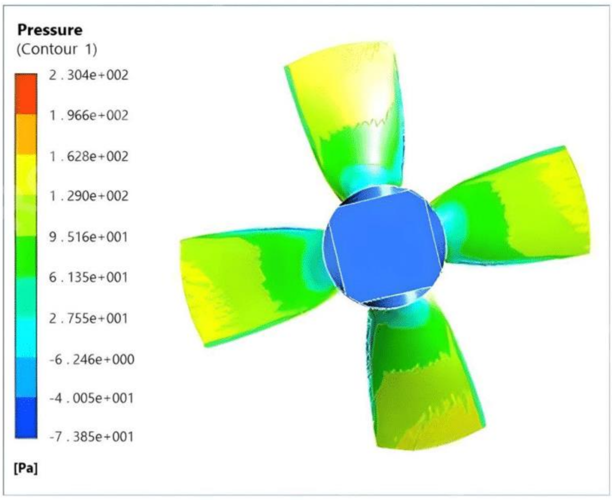


(c)

Fig. 5. Distribution of back surface pressure of Ka-Z3 (a) ϴ = 10.3^o (b) ϴ = 15.3^o (c) for ϴ = 20.0^o



(a)



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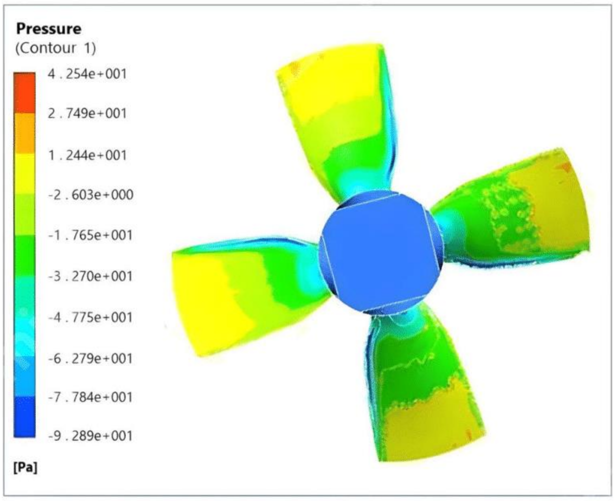
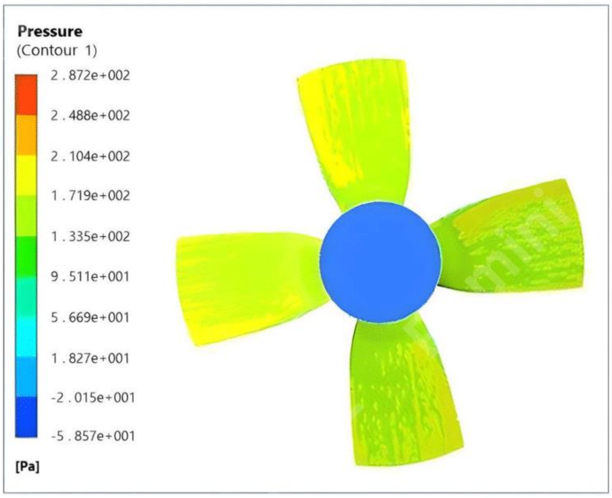
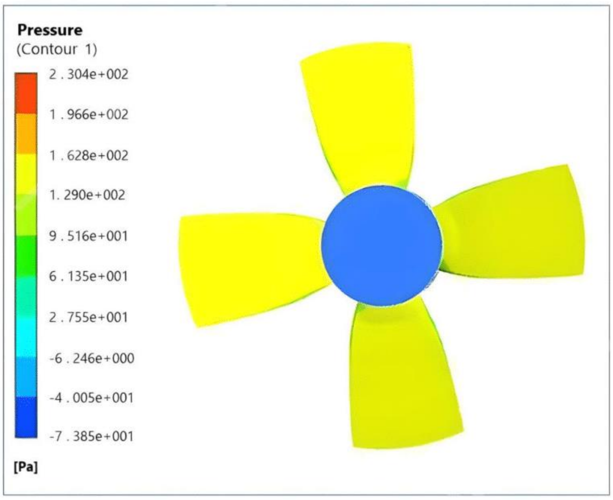


(c)

Fig. 6. Distribution of face surface pressure of Ka-Z4 (a) ϴ = 10.3^o (b) ϴ = 15.3^o (c) for ϴ = 20.0^o



(a)



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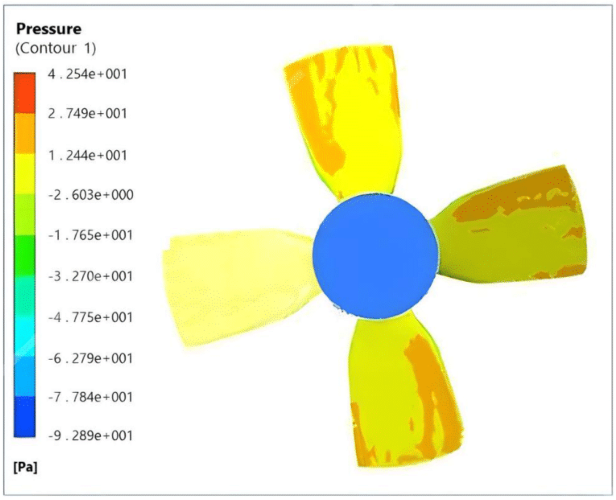
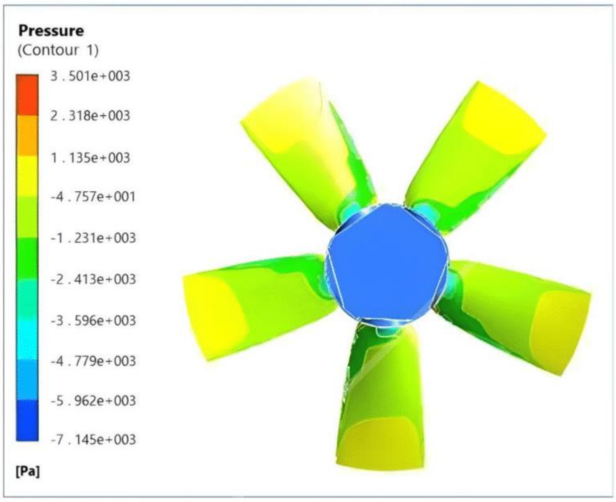


(c)

Fig. 7. Distribution of back surface pressure of Ka-Z4 (a) ϴ = 10.3^o (b) ϴ = 15.3^o (c) for ϴ = 20.0^o



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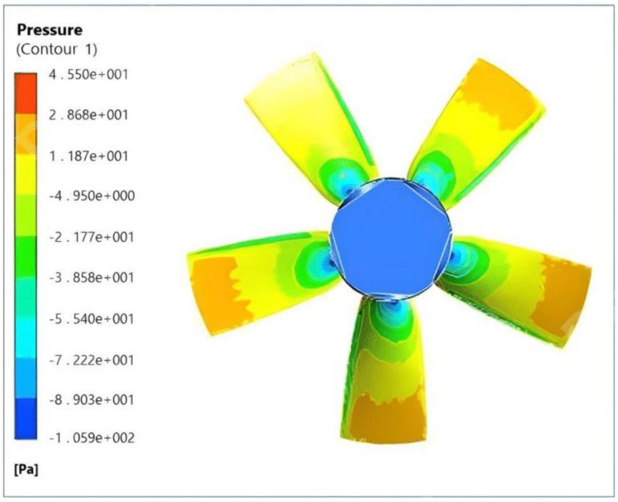

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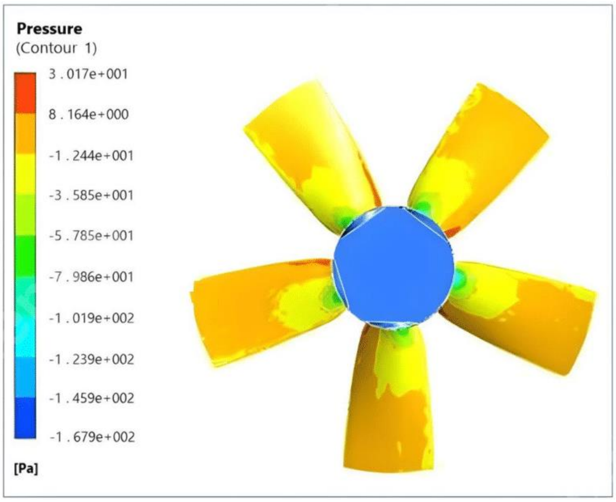
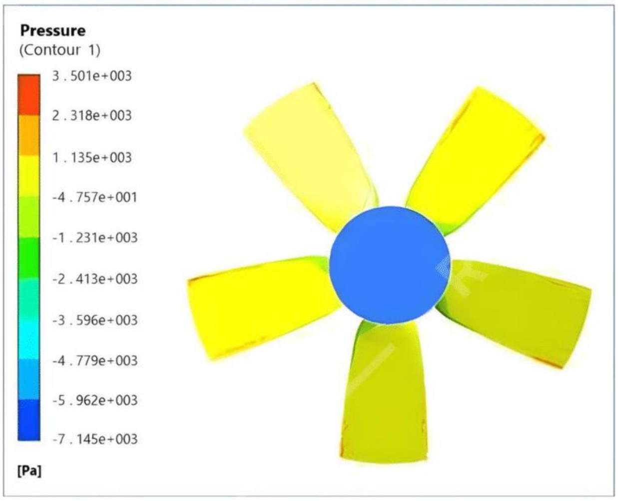
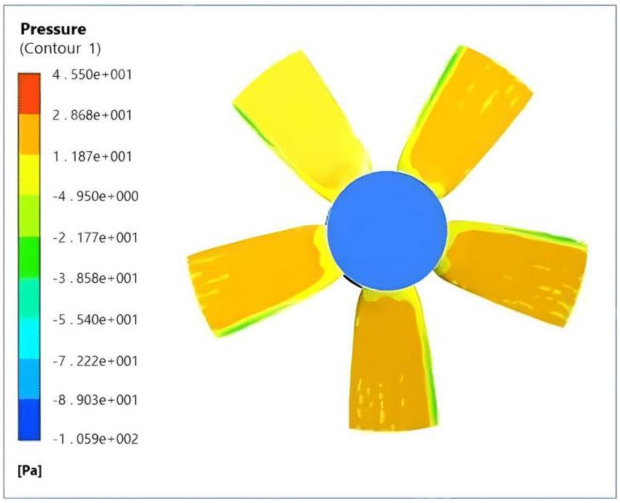


(c)

Fig. 8. Distribution of face surface pressure of Ka-Z5 (a) Ɵ = 10.3⁰ (b) Ɵ = 15.3⁰ (c) for Ɵ = 20.0⁰



(a)



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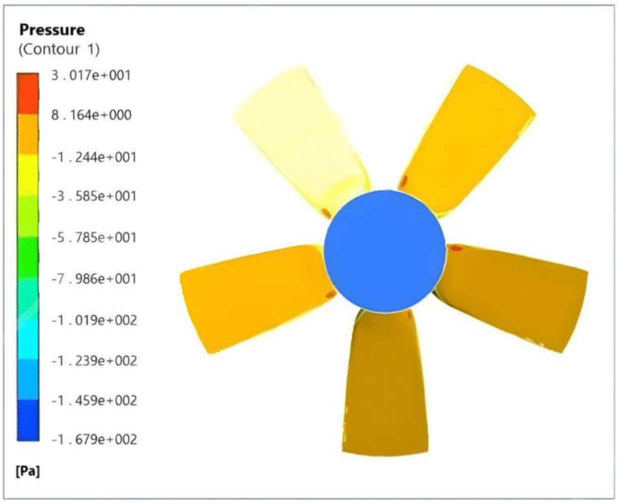

(c)

Fig. 9. Distribution of back surface pressure of Ka-Z5 (a) Ɵ = 10.3⁰ (b) Ɵ = 15.3⁰ (c) for Ɵ = 20.0⁰

3.2 Characteristics of Thrust

Since there is a significantly different in the distribution of pressure surface based on the simulation results, it gives an impact to the thrust and torque that is generated due to the influence of the Ɵ and number of blade variations. The simulation results for the thrust based on the model's variations of Ka-Z3, Ka-Z4, and Ka-Z5 with Ɵ = 10.3^o, Ɵ = 15.3^o, and Ɵ = 20.0^o are shown in Figure 10.

Figure 10 shows the thrust generated from the Ka-Z3, Ka-Z4, and K5-Z5. However, it depicts that the higher angle of attack increases the propeller thrust. Besides, the mode blade number slightly decreases the propeller thrust and the decrease ratio is obviously at a higher angle of attack. It is possible due to the surface area with a smaller number of blades has a higher surface area thus increasing the propeller thrust. Moreover, the high angle of attack simultaneously increases the propeller thrust.

The high angle of attack and lower blade number is generally shown the highest results. It shows that the highest thrust for the overall models was produced by the Ka-Z3 at Ɵ = 20.0^o. Hence, the thrust force is equal to the blade area multiplied by the difference in pressure. Therefore, the force of the Ka-3 models is relatively high, it is possibly due to the wide blade area owned by the model compared with the other model. Higher each blade surface area swipes more fluid to generate thrust.

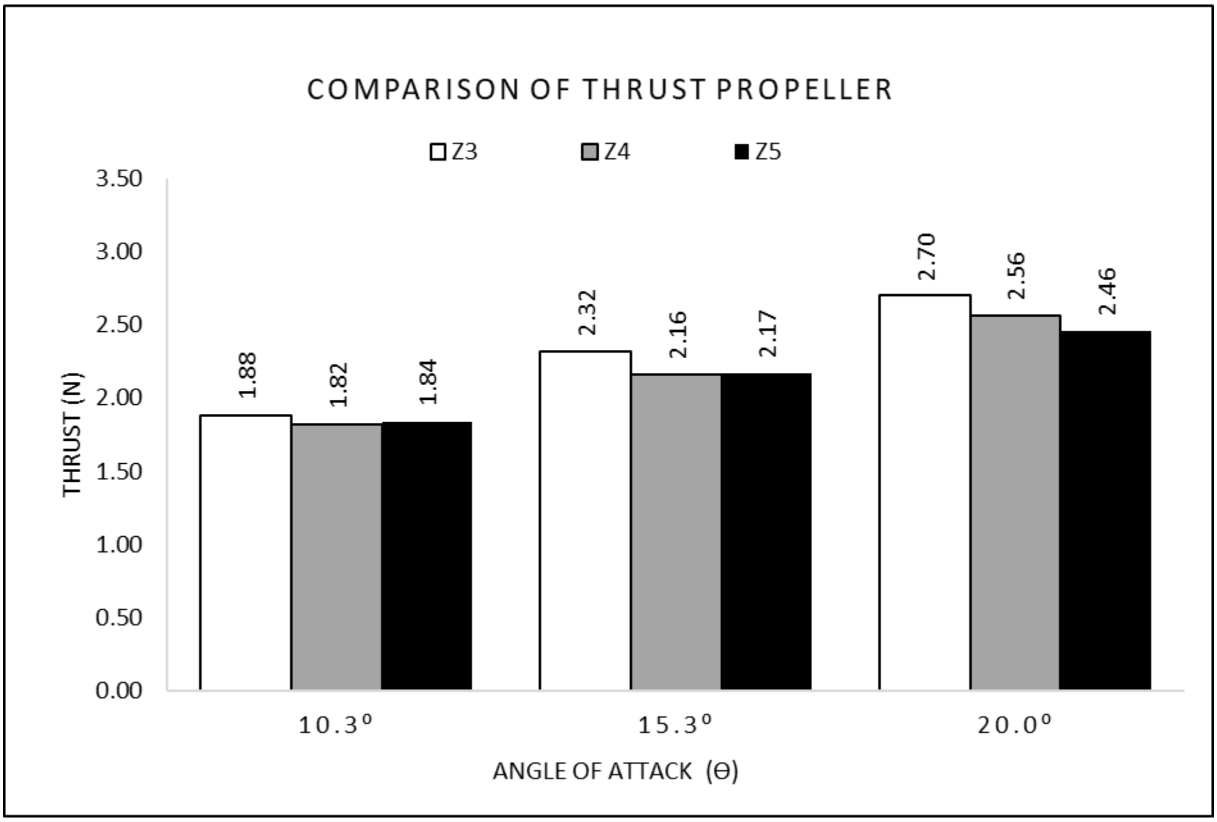

Fig. 10. Comparison of thrust for Ka-Z3, Ka-Z4, and Ka-Z5

3.3 Characteristics of Torque

The simulation results for the torque based on the model's variations of Ka-Z3, Ka-Z4, and Ka-Z5 with Ɵ = 10.3^o, Ɵ =15.3^o, and Ɵ = 20.0^o are shown in Figure 11. The results showed that the toque of the propeller model variations is not significantly different, with the highest result produced by the Ka-Z5 with Ɵ = 20.0^o. The torque value between the angle of attack 10.3^0 and 15.3^0 has similar results, only on a high angle of attack 20.0^{o} with Ka-Z4 has a slight difference than the other angle of attack. This condition is possible due to the surface area between the variations being similar to ensure the torque has the same value. However, in this case, result, the torque value can be ignored due to the insignificant value between the variations of the number of blades and angle of attack. Besides, this condition is necessary to identify another effect of the propeller variations.

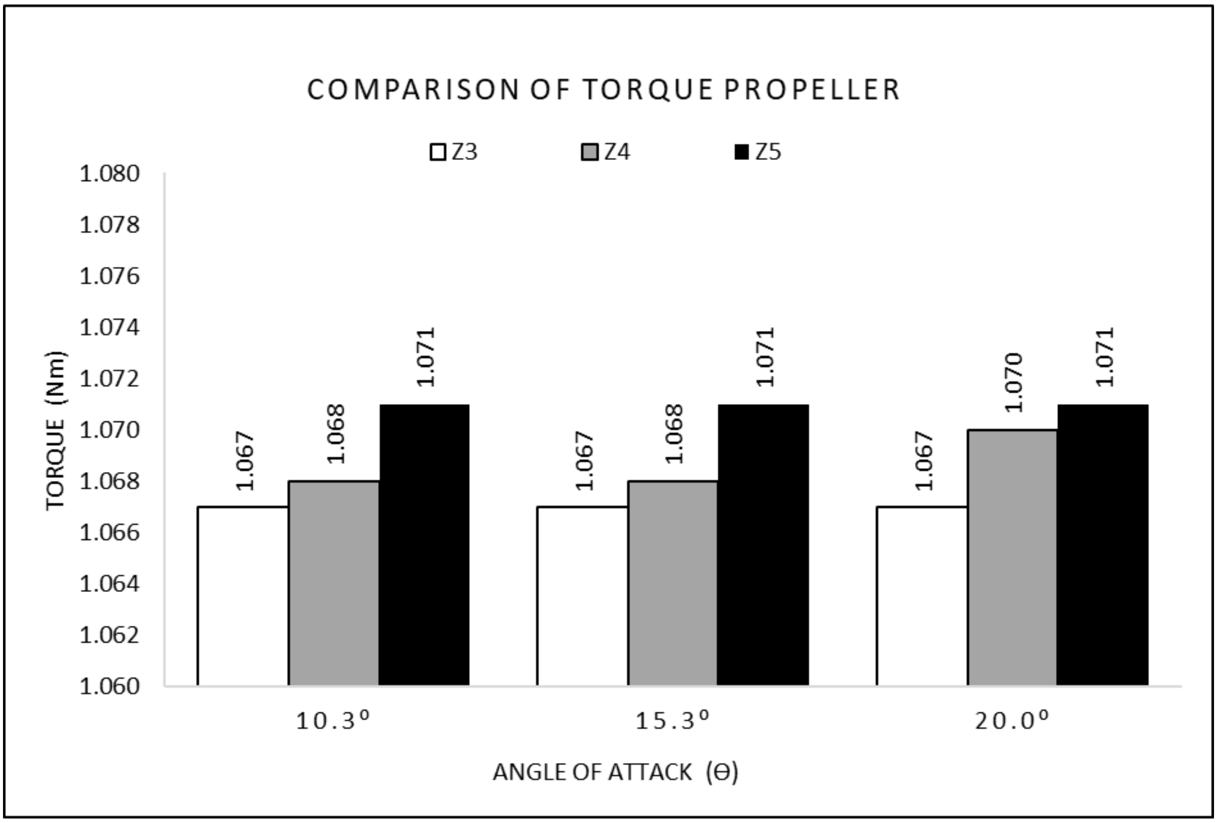

Fig. 11. Comparison of torque for Ka-Z3, Ka-Z4, and Ka-Z5

3.4 Characteristics of Propeller Efficiency

Figure 12 depicts the propeller Ka-Z3, Ka-Z4, and Ka-Z5 efficiency comparison with variations in the angle of attack Θ = 10.3^{o}, Θ = 15.3^{o}, and Θ = 20.0^{o}. However, a higher angle of attack increases the propeller efficiency. It is possible due to the higher thrust achieved at a higher angle of attack. As mentioned before, the higher angle of attack increases the propeller pitch thus higher thrust is developed and higher surfaces swipe the propeller blades thus increasing the propeller efficiency. Besides, the higher number of propeller blades lowers the propeller efficiency. The low number of propeller blades increases the blade surface area thus the fluid is gradually flowing through the propeller blades which increases the propeller thrust and torque thus increasing the propeller efficiency.

However, the effect of propeller blade number has a low effect on propeller efficiency with a low angle of attack variations. Besides, it significantly affects the efficiency at a high angle of attack. At a low angle of attack, the number of blades with Ka-Z4 has a lower propeller efficiency than others even with insignificant value. It indicates that a low angle of attack requires a proper number of propeller blades. Although, in this case, the variation in the propeller efficiency is very low at a low angle of attack. It is possible to significantly increase other variations which can be evaluated in future studies.

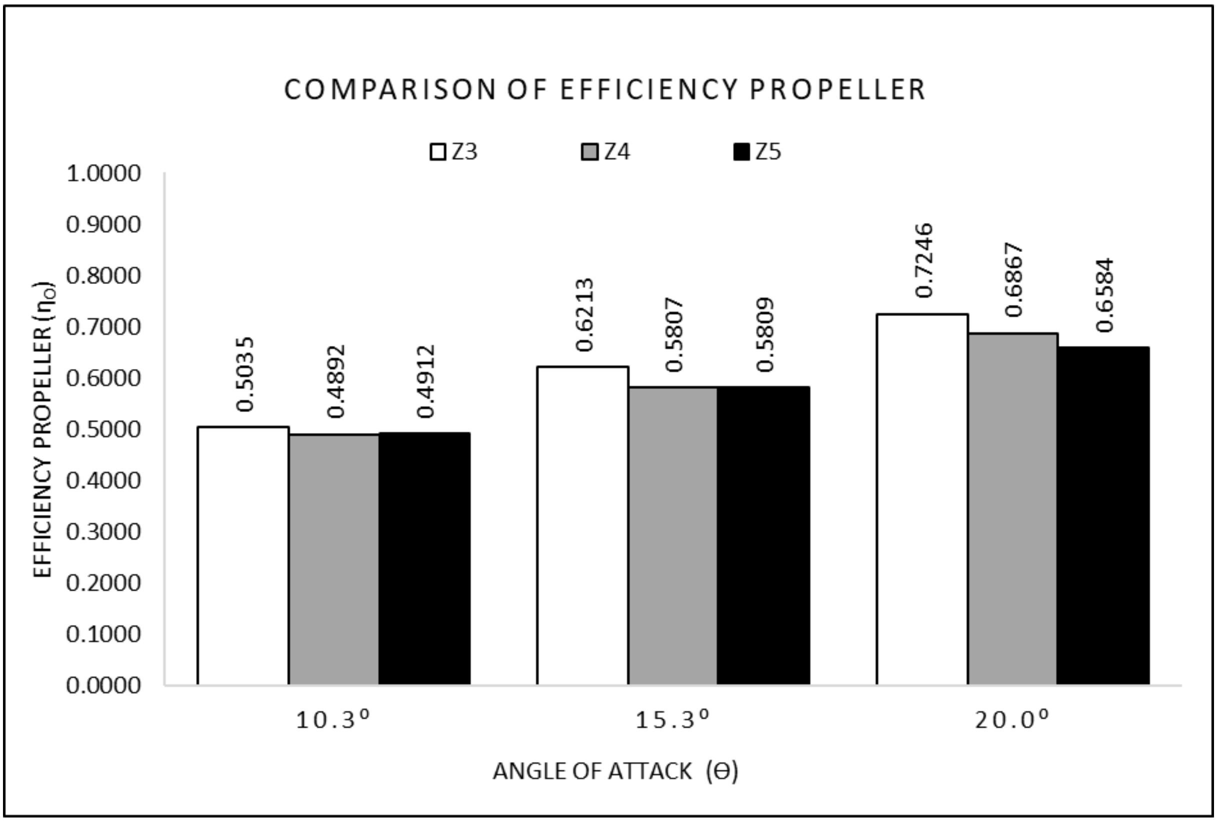

Fig. 12. Comparison of propeller efficiency for Ka-Z3, Ka-Z4, and Ka-Z5

4. Conclusion

The Kaplan series propeller in this study is simulated by using CFD due to the effect of angle of attack and number of blade variations on propeller performance. The numerical study is carried out by variating the Ka series (Ka), with the number of blades Z= 3, 4, and 5, with diameter *D*= 30, and angle of attack ϴ= 10.3°, 15.3°, and 20.0° respectively. The result obtained by the simulation shows that the results distribution of pressure surface, thrust, and torque increased due to the change of angle of attack ϴ. The distribution of pressure surface, thrust, and torque tend to increase at the higher ϴ. However, it tends to be decreased by the higher blade number Z. The CFD results show that the highest thrust and efficiency were generated by the Ka-Z3 with ϴ=20.0° but the torque is low. However, Ka-Z4 with ϴ=20.0° is considerable to obtain the best performance due to insignificant value differences in thrust and efficiency with higher torque.

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