



Effect of Angle of Attack on Lift, Drag, Pitching Moment and Pressure Distribution of NACA 4415 Wing

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ABSTRACT

This experiment was conducted to determine the effects of angle of attack on lift, drag, pitching moment and pressure distribution during the flow of NACA 4415 wing model of chord length of 200mm, leading edge radius of 4.96mm and span of length 450 mm using a low speed open return wind tunnel with test section of 0.47m width, 0.47m height and 1.27m length. The wing model was subjected to several tests at two different speeds of 15m/s and 25m/s which corresponds to two different Reynolds numbers of 1.8×10^5 and 3.1×10^5 respectively. The result showed that for both speeds, the coefficient of lift increased as angle of attack increased and the maximum lift coefficient was 1.45 at 15m/s while at 25m/s, the coefficient of lift is 1.40, which is slightly less than that at 15m/s. The coefficient of drag also increased as the angle of attack increased from 0° to 18° and the maximum drag was 0.15 at 15m/s, while at 25m/s, the coefficient of drag is approximately 0.2 which showed that the wing has a very low drag coefficient. For pressure distribution, it was observed that there was no flow separation at low angle of attacks from -6° to 0° , but the flow began to separate at moderate angle of attack of 3° to 9° and fully separated at high angle of attacks of 12° to 18° with vortices for both speeds.

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INTRODUCTION

A fluid flowing over an object has a tendency to drag the object along its flow direction. An object passing through a fluid which is stationary, there is a tendency to slow the object down. For a stationary object in a fluid which is flowing, there is a tendency to move the object in the fluid flowing direction. These tendencies of flowing fluid is known as drag (Yeung 2006). An airplane is a vehicle with wings and one or more engines that enable it to fly through the air and any section of the wing cut by the plane which is perpendicular to the wing is called an airfoil. Airplane wings produce lift by creating pressure difference

between top surface and bottom surface (Seifert 2002). For an object passing through a fluid which is stationary there is a tendency to slow the object down. While moving through air, airplanes also are subjected to several drags. In order to overcome these drags airplane wings cross section airfoils are designed and studied for many years. Ludwig Prandtl in the year of 1917 made a wind tunnel at Gottingen which is capable of testing large airfoil sections. He also had a model which is based on mathematics to generate airfoil like curves. National Advisory Committee for Aeronautics, or NACA, in the year of 1930 prepared and investigate "families" of airfoils.

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Some of the very popular of these were the NACA four-digit and five-digit series. NACA's six digit airfoil 23000 series which was prepared in 1935, is assumed to be the most widely used airfoil in history (Rubiati 2017).

One of the models that was developed by NACA includes the four digit wings such as NACA 4415, which is one that was investigated in these research. The lift, drag, pitching moment and pressure distribution along all the parts of the wing were analyzed using a low speed wind tunnel. The airfoil profiles of all NACA families are obtained by merging a mean line and a thickness distribution (Brzozowski et al 2008). The needed coordinates for the distribution of mean lines and thickness is obtained from the available sources. The available sources provides with necessary coordinates. The way of merging a mean line and a thickness distribution to produce the required airfoil profile is shown by below mentioned figure. (Munday and Jacob 2008) constructed an adaptive wing with conformal camber on the base profile of a NACA 4415 airfoil to control the separation. This wing uses an actuator which changes the shape of the airfoil surface. They conducted the experiments for different angles of attack and Re between 2.4×10^5 and 2×10^5 . They demonstrated that use of the adaptive wing could decrease the separation. In another work, they extended their approach by comparing the numerical and experimental results using the adaptive wing technology. Timmer (2008) conducted flow visualization studies of corrugated airfoils using steps to compare them with conventional Joukowski airfoil by incorporating a backward facing step based on conformal mapping calculations.

The results were in favor of the corrugated airfoils confirming that stepped airfoils produced better lift characteristics due to the formation of vortices. Triple corrugated airfoils produced as much as 10

% more than their conventional counterparts for the same camber, thickness and angle of attack. (Pankaj and Neelash 2016) also used CFD to investigate the behavior of NACA 4415 and also, to determine a suitable angle of attack for it under different angle of attacks. In the research, CFD ansys fluent software was used over the NACA 4415. The CFD analysis was done for angles of attack 12° , 14° , 16° and 18° at Reynolds Numbers 1000000 and 1500000. It was found that as the angle of attack increases, the coefficient of lift also increases, but after 16° coefficient of lift, it started to reduce due to adverse pressure gradient at the trailing edge. (Gregorio and Fraioli 2008) conducted an experimental study of flow control using a trapped vortex cavity on a high thickness airfoil with an objective to apply the results obtained to blended wing designs. Data from PIV measurements showed that passive Trapped Vortex Control (TVC) flow control is neither an effective separation control mechanism nor capable of confining the vortex and controlling the vortex shedding. On the other hand, active flow control is capable of controlling flow separation. Despite all the efforts made by the afore mentioned researchers, to the best of our knowledge, the effect of angle of attack on lift, drag, pitching moment and pressure distribution of NACA 4415 wing model at the speed of 15m/s and 25m/s with corresponding Reynolds number of 1.8×10^5 and 3.1×10^5 has not been investigated. Therefore, this research fills the outlined gap. The aim of the research is to investigate the flow behavior of NACA 4415 and the objectives include, to determine the data balance (lift, drag and pitching moment) on the wing model and to determine the pressure distribution along the wing model.

MATERIALS AND METHOD

The Wing Model: The model was designed by combining about five (5) different models

with spherical outward, spherical inward, hexagonal, circular and combination of circular and hexagonal dimples all together in order to produce the model. The detailed

dimension of the NACA 4415 wing model. It has a chord length of 200mm, leading edge radius of 4.96mm and span of length 450 mm.

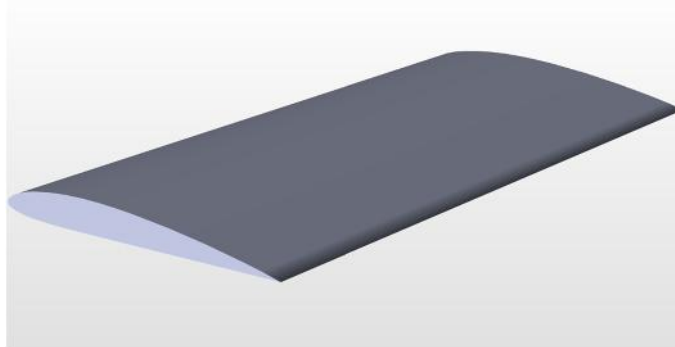


Figure 1: Three dimensional drawing of the wing model

The Wind Tunnel: The experiment was conducted in the wind tunnel of the department of Aerospace Engineering in Universiti Teknologi Malaysia. It was a medium sized open return type wind tunnel. The test section is 0.47m (width) x 0.47m

(height) x 1.27m (long). The low speed wind tunnel measures wind speed at a low speed and it operates base on continuity and Bernoulli's equation. The figure below shows the UTM low speed open return wind tunnel.



Figure 2: UTM low speed open return wind tunnel

Model Installation: The wing model was installed inside the test section with the help of a support mechanism inside the test section. The wing was bolted from its

adjacent side in order not to interfere with the flow of air that will be passing through the wing model.



Figure 3: Installed wing model in the open return wind tunnel

Test Configuration: The experiment was conducted for two speed 15m/s and 25 m/s which has values of Reynolds number 1.8×10^5 and 3.1×10^5 respectively and the angle of attack was varied from -6° to 18° . The experimental conditions are shown in Table (2) below. Two measurement methods were used on the model, namely steady balance data and flow visualization

techniques. In order to visualize the flow above the wing, tuft method was employed. Figure below shows the tuft setup in the wind tunnel. This method is done by using several arrays of threads that had been tied to the net. This tuft has been placed in front of the model. This method can detect the development of the primary vortex and it helps us to indicate the flow chaotic.



Figure 4: Tuft set up in the wind tunnel

Table 1: Test parameters

Method	Steady Balance Measurement	Steady Balance Measurement
Reynolds Number	1.8×10^5	3.1×10^5
Speed	15 m/s	25 m/s
Angle of attack	-6, -3, 0, 3, 6, 9, 12, 15, 18.	-6, -3, 0, 3, 6, 9, 12, 15, 18.

RESULTS AND DISCUSSION:

The experiment was carried out in UTM low speed wind tunnel on NACA 4415 aerofoil to obtain the value of the aerodynamic forces coefficient which are lift coefficient, drag coefficient, pitching moment coefficient and pressure coefficient. The experiment was conducted at two different speeds, corresponding to Reynolds number of 1.8×10^5 and 3.1×10^5 and the angle of attack varies from -6° to 18° with three angles difference. This section discussed the results obtained.

Aerodynamic Characteristics at $Re\ 1.8 \times 10^5$

It can be seen that the lift coefficient which is shown in Figure 4.1 continuous to increase as the angle of attack increases gradually. The maximum lift coefficient at Reynolds number 1.8×10^5 for

the NACA 4415 is around 1.45 at 18° angle of attack. The drag coefficient which is shown in Figure 4.2 also increases gradually as the angle of attack is increase. The maximum drag coefficient achieved for this aerofoil is about 0.15 at 18° angle of attack. The pitching moment coefficient is shown in Figure 4.3. Increase in the angle of attack decreases the moment coefficient value gradually which is opposite to lift and drag forces. From -6° to 0° , the coefficient of moment decreases while from 0° to 6° , it increases and lastly from 6° to 18° , the coefficient of moment continued to decrease. Comparing lift coefficient to drag coefficient as shown in Figure 4.8, NACA 4415 shows insignificant effect at higher speed compared to lower speed where this aerofoil has high lift coefficient value and low drag coefficient value.

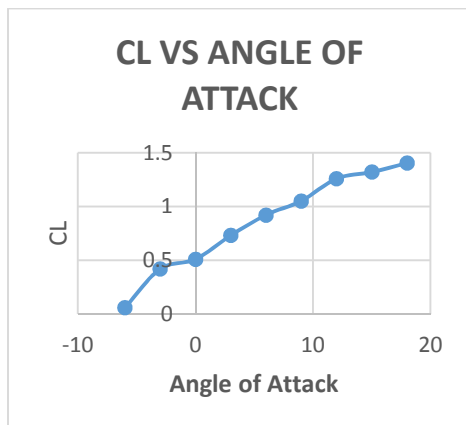


Figure 5: Variation of angle of attack with Coefficient of lift

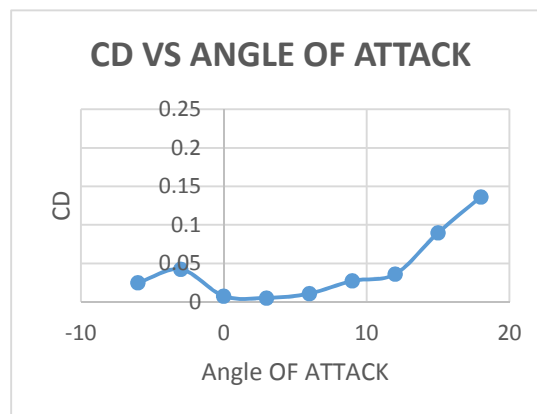


Figure 6: Variation of angle of attack with Coefficient of drag

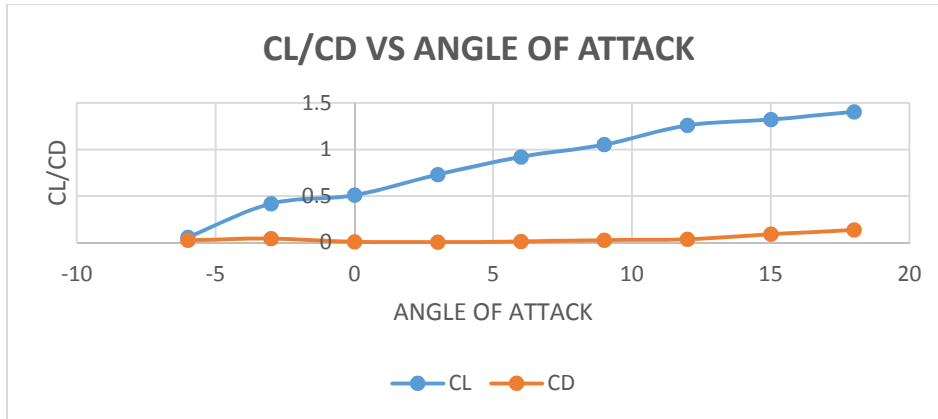


Figure 7: Variation of angle of attack with coefficients of lift and drag

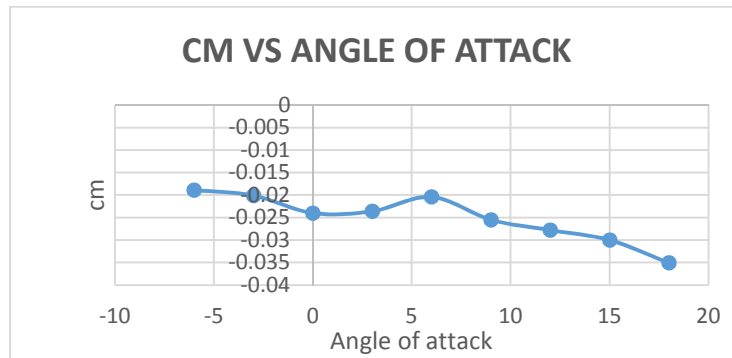


Figure 8: Variation of angle of attack with coefficient of moment

Aerodynamic Characteristics at $Re\ 3.1 \times 10^5$

When the Reynolds number was increased, as the aerodynamic characteristics has no significant effect on the lift, drag and moment coefficient. Figure 4.5 shows the lift coefficient against angle of attack, as the angle of attack increase the lift coefficient increase gradually, the maximum lift was about 1.40 at 18° which is slightly less than that at 1.8×10^5 Reynolds number. Figure 4.6 shows the drag coefficient, increasing the angle of attack increases the drag coefficient gradually where drag is increasing proportionally to lift, the maximum drag recorded at 18° was observed to be approximately 0.20, which is higher than that at 1.8×10^5 Reynolds

number. The pitching moment coefficient is shown in Figure 4.7. Increase in the angle of attack decreases the moment coefficient value gradually which is opposite to lift and drag forces. From -6° to 0° , the coefficient of moment decreases while from 0° to 6° , it increases and lastly from 6° to 18° , the coefficient of moment continued to decrease. As it can be seen, the same behavior was exhibited also for the coefficient of moment at 1.8×10^5 . Comparing lift coefficient to drag coefficient as shown in Figure 4.8, NACA 4415 shows insignificant effect at higher speed compared to lower speed where this aerofoil has high lift coefficient value and low drag coefficient value.

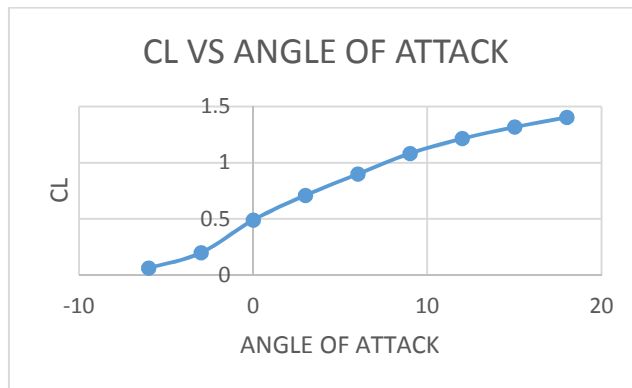
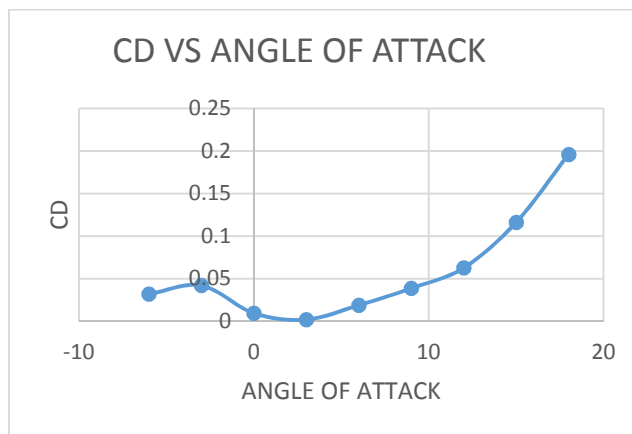


Figure 9 Variation of angle of attack with coefficient of lift



10: Variation of angle of attack with coefficient of drag

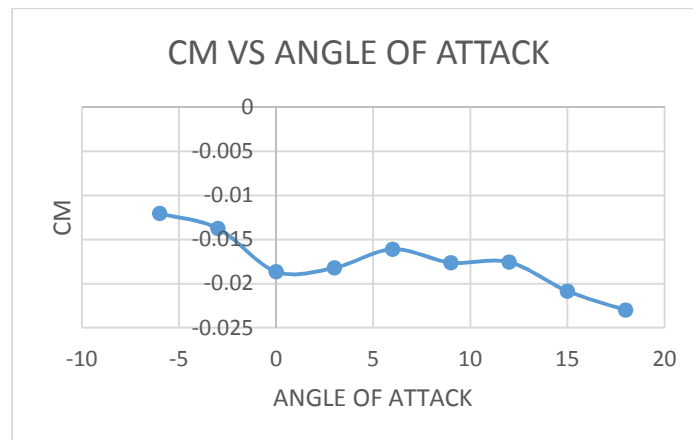


Figure 11: Variation of angle of attack with coefficient of moment

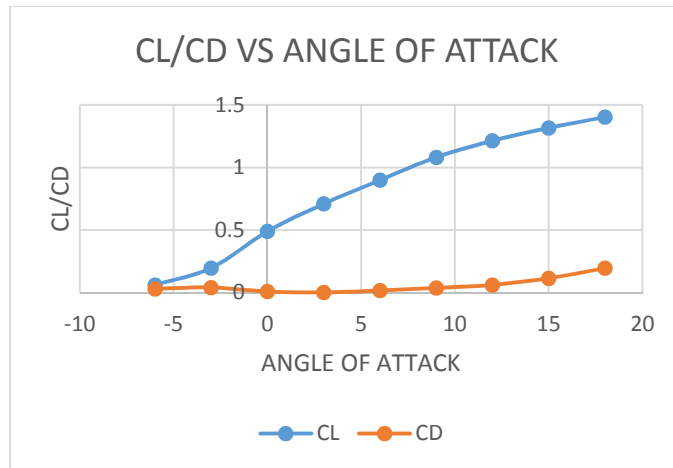


Figure 12: Variation of angle of attack with coefficients of lift and drag

PRESSURE DISTRIBUTION RESULTS

The results obtained from the pressure distribution experiment illustrate the following; at Reynolds number of 1.8×10^5 and low angles of attack which varies from -6° to 0° the flow was not separated thus no suction peak is indicated as shown in Figure 4.9 and Figure 4.10. At low to moderate angle of attack the flow separated at the leading edge and suction peak is indicated as shown in Figure 4.11 and Figure 4.12 below. Therefore the primary vortex strength decreases as it travels downstream. Further increase in angle of attack increases the size of the separated flow region which

indicate strong vortex formation at the leading edge as shown in Figure 4.13 and Figure 4.14 below. This is in agreement with (Rubiat et al 2015) whereby they investigated the effect of different shaped dimples on airfoils. They also observed that there was no flow separation at 0° angle of attack for both the regular and dimpled airfoil they used but as the angle of attack increases from 0° to 12° , flow separated began to occur on the regular shaped model while for the dimpled, it didn't occur. Further increase in the angle of attack from 12° , resulted in a clear flow separation which occurs at the upper surface of the airfoil.

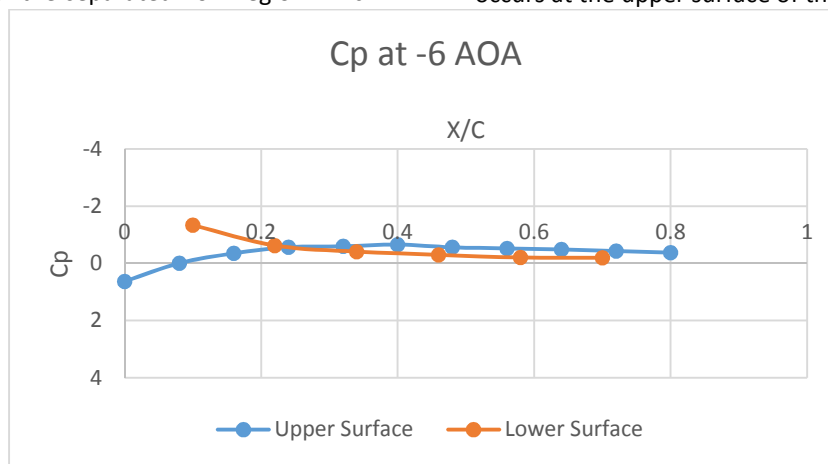


Figure 4.9: Pressure coefficient vs. x/c at $Re = 1.8 \times 10^5$.

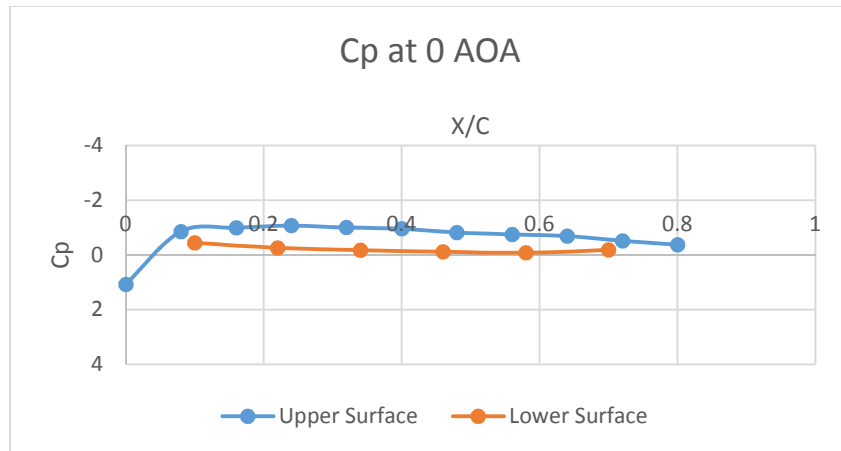


Figure 4.10: Pressure coefficient vs. x/c at $Re = 1.8 \times 10^5$.

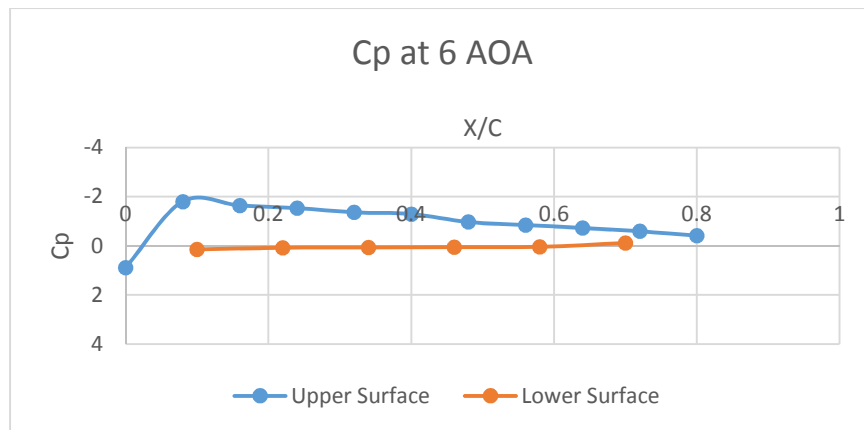


Figure 4.11: Pressure coefficient vs. x/c at $Re = 1.8 \times 10^5$.

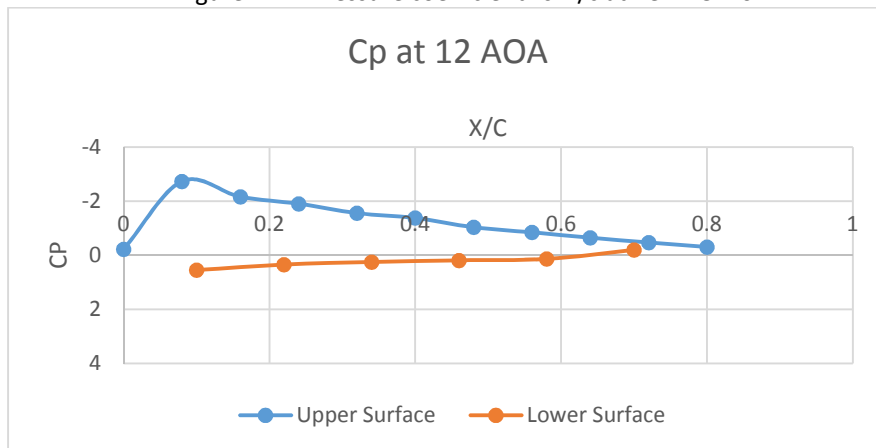


Figure 4.12: Pressure coefficient vs. x/c at $Re = 1.8 \times 10^5$.

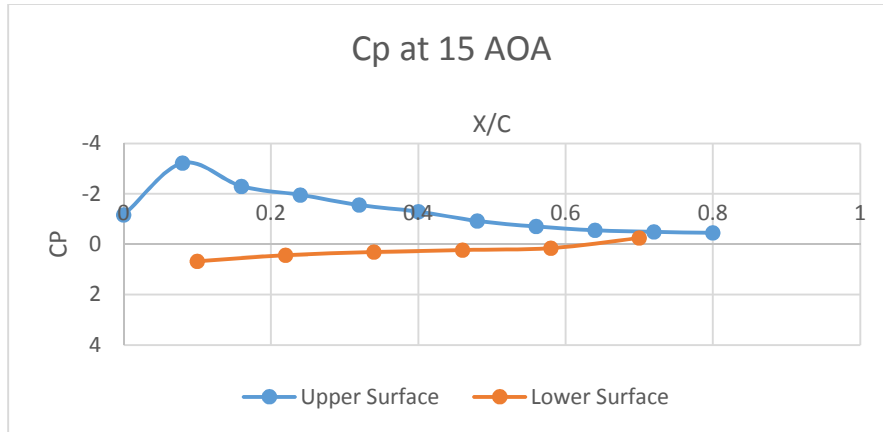


Figure 4.13: Pressure coefficient vs. x/c at Re= 1.8x10⁵.

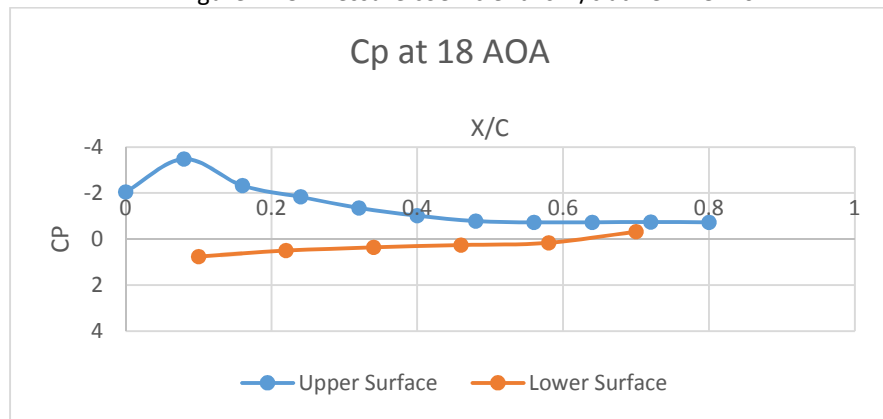


Figure 4.14: Pressure coefficient vs. x/c at Re= 1.8x10⁵.

Further increase in Reynolds number has a slight effect on the development of the primary vortex due to increasing in the viscosity of the attached flow. At angle of attack of -6° and 0° shows is similar behavior where the flow remains attached without indication of separation as shown in Figure 4.15 and Figure 4.16 below. At low to moderate angle of attack the flow separated at the leading edge and suction peak is indicated as shown in Figure 4.17 and Figure

4.18 below. Therefore the primary vortex strength decrease as it travels downstream. Further increase in angle of attack increases the size of the separated flow region which indicate strong vortex formation at the leading edge as shown in Figure 4.19 and Figure 4.20 below. This is in agreement to (Deng 2007), who investigated flow separation control around an airfoil using pulsed jets. The flow separated at high angles of attack.

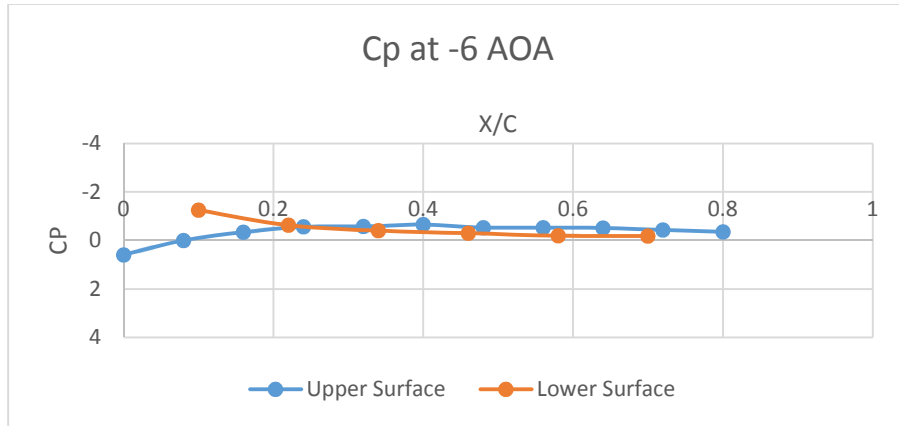


Figure 4.15: Pressure coefficient vs. x/c at $Re= 3.1 \times 10^5$.

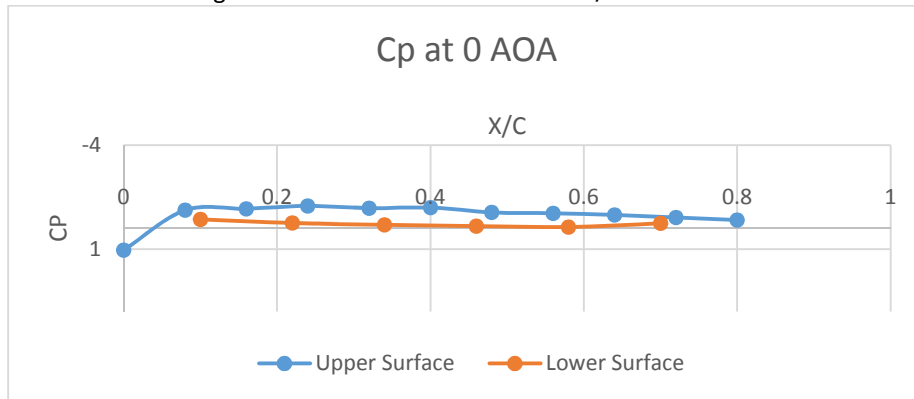


Figure 4.16: Pressure coefficient vs. x/c at $Re= 3.1 \times 10^5$.

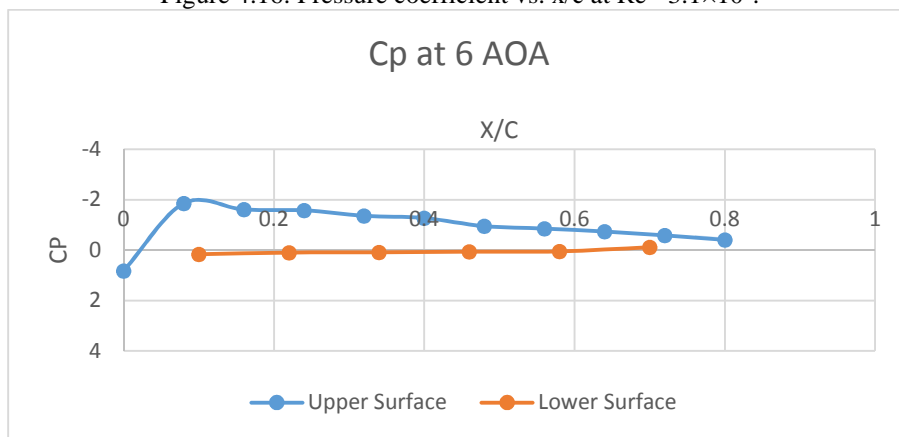


Figure 4.17: Pressure coefficient vs. x/c at $Re= 3.1 \times 10^5$.

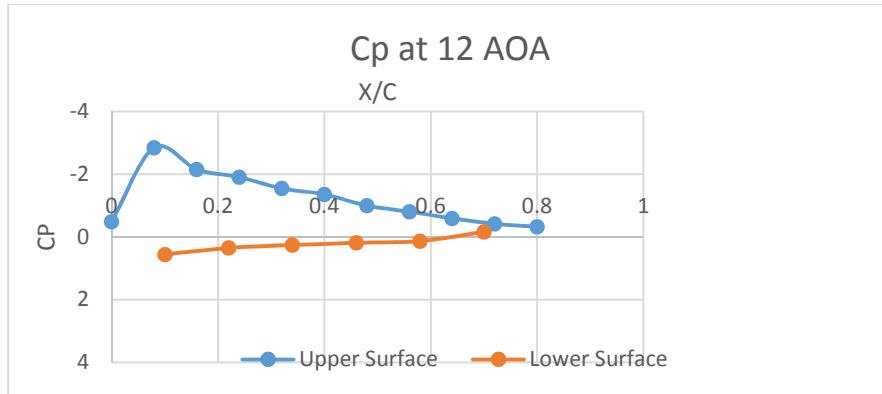


Figure 4.18: Pressure coefficient vs. x/c at $Re= 3.1 \times 10^5$.

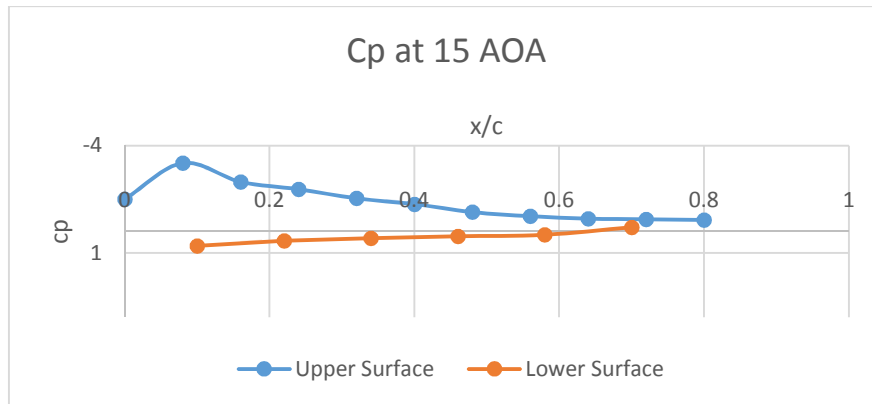


Figure 4.19: Pressure coefficient vs. x/c at $Re= 3.1 \times 10^5$.

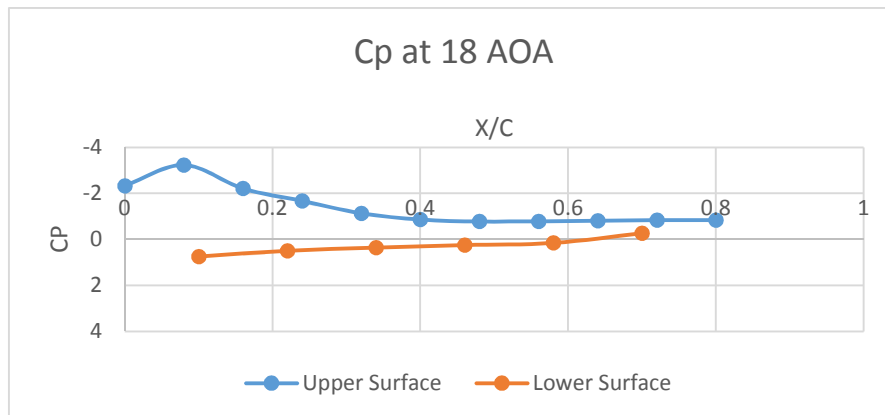


Figure 4.20: Pressure coefficient vs. x/c at $Re= 3.1 \times 10^5$.

CONCLUSION

The experiment conducted using the low speed wind tunnel on NACA 4415

aero foil at two different speeds, corresponding to 1.8×10^5 and 3.8×10^5 Reynolds number and the angle of attack

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varies from -6° to 18° . Balance data such as lift, drag and pitching moment were determined. Also, pressure distribution along the wing model were also determined in the experiment. The result shows that NACA 4415 aerofoil has a very high lift coefficient and a very low drag coefficient, which is reason why it is used for several applications such as in blades of wind turbine or in aircrafts. The maximum lift coefficient was found to be 1.45 and the maximum drag coefficient was found to be 0.15 at 15m/s and maximum lift coefficient of 1.40 and drag coefficient of approximately 0.2 at 25m/s, which indicates that the wing has greater lift and lower drag at 15m/s when compared to 25m/s. This clearly shows that the wing is more efficient at lower speed than higher speed even though the difference is not much and explains the special characteristics of the wing model. For the pressure distribution along the wing model, the result shows that there is attached flow at low angle of attacks i.e. from -6° to 0° while from 3° upward, there is flow separation and it increases as the angle of attack increases for both speeds, this is why minimal angle of attack are preferred while using the NACA 4415 aerofoil.

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