# AERODYNAMICS STUDY OF TUBERCLE EFFECT ON NACA4412 AIRFOIL

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# DECLARATION

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### CHAPTER 4: RESULT AND DISCUSSION

# ABSTRAK

## Tajuk

Kajian Aerodinamik Terhadap Kesan Bonggol Pada Aerofoil NACA4412

Tujuan kajian in adalah untuk mengkaji ciri-ciri aerodinamik aerofoil NACA4412 yang mempunyai kesan bonggol pada pinggir depan aerofoil. Kajian ini dijalankan ke atas tiga pinggir depan aerofoil yang berbeza; pinggir depan tanpa kesan bonggol, pinggir depan dengan bonggol sfera dan pinggir depan dengan bonggol sfera yang berterusan. Kajian ini menumpukan terhadap kesan bonggol sfera tersebut ke atas ciri-ciri aerodinamik aerofoil NACA4412 seperti daya angkat dan seret. Eksperimen telah dijalankan dengan menggunakan terowong angin di makmal aerodinamik di Universiti Sains Malaysia. Keputusan yang diperoleh telah dibandingkan dan dibincangkan dengan lebih lanjut dalam tesis.

# ABSTRACT

## Title

Aerodynamics Study of Tubercle Effect on NACA4412 Airfoil

The purpose of this research is to study the aerodynamics characteristics of NACA4412 airfoil with tubercle effect on its leading edge. The study was performed on three different leading edges of the airfoil; leading edge without the tubercles, leading edge with spherical tubercles and leading edge with continuous spherical tubercles. The study focuses on the effect of the spherical tubercles on aerodynamics lift and drag characteristics of the NACA4412 airfoil. The experiment was performed by using the wind tunnel in the aerodynamics laboratory in Universiti Sains Malaysia. The result was obtained, compared and discussed further in the thesis.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

According to Merriam-Webster dictionary, a tubercle is a small knobby prominence or excrescence especially on a plant or an animal. A Humpback whale (*Megaptera novaeangliae*) has tubercles on its flippers which believed to help it to be more maneuverable in the water in order to capture preys easily.

In the late 2000s, the tubercle effect on the Humpback whales' ability to perform tight turning maneuvers led Dr. Frank E. Fish to discover the effect of tubercles on the leading edge of an airfoil can improve its aerodynamics. The tubercles on the airfoil's leading edge channel the airflow over the airfoil into more narrow streams which creates higher velocities.

The tubercle effect also reduce the airflow moving over the wing-tip, which resulting in less parasitic drag due to wingtip vortices. Dr. Fish early studies also suggested that the tubercles delayed stall and improved lift by energizing the boundary layer in a way that is comparable to the way that vortex generators operate.

Due to the way the tubercles produce favorable aerodynamics performance, it is anticipated that the tubercle effect will be widely used in the development of airfoils in the aviation industry.

## 1.2 Problem Statement

One of the problems encountered in the project was during the mounting of the airfoil NACA4412 model in the open circuit wind tunnel used. The test section of the wind tunnel comes with acrylic covers where one cover has a hole used to mount the airfoil model. This hole is then covered with tapes after the model is mounted. This might contribute to the inaccuracy in the results obtained during the test.

Another problem encountered when the spherical tubercles made of modeling clay would sometime fell off the leading edge of the airfoil during the wind tunnel test. This problem is solved by smoothing the edges of the spheres against the surface of the leading edge of the airfoil.

The other problem encountered during handling the wind tunnel. The wind tunnel is controlled manually; wherein the velocity of the wind flow is controlled by adjusting the RPM. I needed to go back and forth from the control panel on one side of the wind tunnel to the computer which is on the other side of the wind tunnel to determine the velocity achieved is the one needed for the experiment.

## 1.3 Mission Statement

To study and compare the aerodynamics characteristics of 3 different airfoil NACA4412.

## 1.4 Objectives

The objectives of the project are:

1. To study the aerodynamics performance of airfoil NACA4412 with smooth leading edge.
2. To study the aerodynamics performance of airfoil NACA4412 with tubercles placed a distance apart of each other on its leading edge.
3. To study the aerodynamics performance of airfoil NACA4412 with continuous tubercles on its leading edge.
4. To compare the aerodynamics performance of the 3 airfoils with different leading edge.

## 1.5 Scope of Work

The scopes of work that have to be done for this project are as the following:

1. Perform wind tunnel test on the plain airfoil NACA4412.
2. Place spherical tubercles made of modeling clay with a uniform distance apart on the leading edge of the airfoil NACA4412 and perform wind tunnel test.
3. Place more spherical tubercles in between the ones already on the leading edge of the airfoil and perform wind tunnel test.
4. Obtain and compare the results from the test.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Airfoil

An airfoil is the shape of a wing of an airplane.[1] It is also the shape of a blade of propeller, rotor or turbine as well as a sail. Aerodynamic force is produced when an airfoil-shaped body is moving through a fluid. Lift is a component of aerodynamic force that is perpendicular to the direction of the motion whereas drag is the aerodynamic force component that is parallel to the direction of the motion.

Cambered airfoil is an asymmetrical airfoil where it can generate lift at zero angle of attack, unlike symmetrical airfoil which requires mostly positive angle of attack to produce lift. The ability of a cambered airfoil to generate lift at zero angle of attack is due to the pressure difference between the upper and lower surface of the airfoil where the airfoil has a higher average velocity on the upper surface than the lower surface.

## 2.2 Humpback Whales

A humpback whale (*Megaptera novaeangeliae*) is a species of baleen whale and is one of the larger rorqual species. It has a distinctive body shape, with a knobbly head and long pectoral fins. The generic name m*egaptera* from Greek words *mega*, which means giant; and *ptera* means wings. This generic name refers to the humpback whale’s large front flippers.

[Figure 1: A humpback whale, *megaptera novaeangliae*]

The flippers of the humpback whales are the longest of any ocean cetacean.[2] The flippers are highly mobile at the shoulder and exhibit some flexibility along their length.[3] Humpback whales utilize these large wing-like front flippers for banking and turning. Large spherical tubercles which are found on the leading edge of their flippers are morphological structures that are very unique in nature. They improve performance and maneuverability of the flipper by acting as passive flow control devices.

[Figure 2: Front flipper of a humpback whale]

The elongate flippers and leading edge tubercles are associated with the feeding methods of the humpback whale where it is the only baleen whale that relies on maneuverability to capture prey.[2] Humpback whales use their flippers as biological hydroplanes to achieve tight turns in conjunction with feeding behaviors.[4] The high lift/drag characteristics of the combination of the tubercles and the high aspect ratio of the flippers favor the sharp, high-speed banking turns executed by the humpback whale while capturing the prey.

A centripetal force necessary to maintain the turn is supplied by a horizontal component of the lift force developed by the flippers.[5][6] Lift and the angle of the bank are inversely related to the radius of the turn.[7][8] To increase the lift to aid in making tighter turns, the angle of attack is increased up to the stalling point. By acting as leading edge control devices to maintain lift and avoid stall at high angles of attack, the tubercles provide an advantage to the humpback whales in maneuverability and in capture of prey. [9]

Hydroplanes used in turning must operate at high angle of attack while maintaining lift.[10] The flippers would stall and the whale would have a reduced centripetal force if the flippers of the whale were canted at too high an angle of attack during a turn. The ability to turn tightly would lost for the whale and the prey could escape.

### 2.3 Tubercle Effect

The tubercle effect is a recently discovered phenomenon where tubercles or large ‘bumps’ on the leading edge of an airfoil can improve its aerodynamics.[11] Dr. Frank E Fish, a professor of Biology from the Department of Biology of the West Chester University, United States, discovered and analyzed this effect in the late 2000s. He first discovered the tubercle effect while conducting a research into why humpback whales have tubercles on the leading edges of their flippers. It is suggested that the tubercles delayed stall and improved lift, contributing to the remarkable agility of the whales.

The tubercle effect creates higher velocities by channeling flow over the airfoil into more narrow streams. Tubercles generate higher lift by energizing the boundary layer in a way that is comparable to the way that vortex generators operate. But, as a rule, tubercles can outperform vortex generators. The reduction of flow moving over the wing-tip is another side effect of these channel, which resulting in less parasitic drag due to wing vortices. When tubercle airfoils operate at higher pitch to generate more lift, they do not incur as great a drag penalty. In fact, tubercle airfoils may incur the lowest drag penalty of any airfoil type as pitch increases. The tubercle airfoils also have an increase in stall angle compared to airfoils without leading edge tubercles.

However, there are some researches conducted where airfoils with tubercles do not perform as well as equivalent airfoils with a smooth leading edge in the pre-stall regime. A research showed that airfoils with leading edge tubercles produced negative effects when at Reynold’s number less than 300,000, while those showing benefits are generally at Reynold’s number greater than 500,000.[12] But it was also observed that airfoils with tubercles experience a much less severe stall and the amount of lift generated in the post-stall regime is higher.[13]

# CHAPTER 3

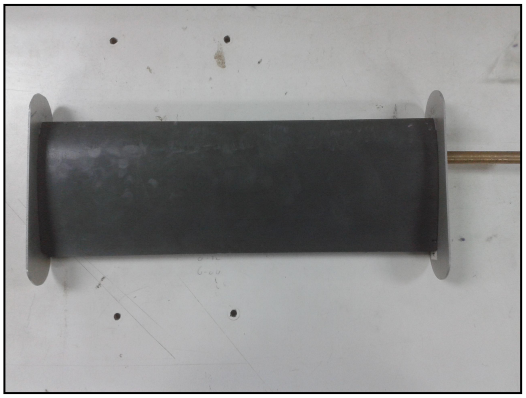
# METHODOLOGY

## 3.1 Apparatus

[Figure 3: Open circuit wind tunnel]

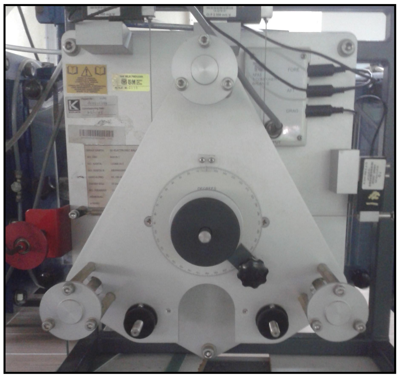
For the wind tunnel test of the airfoil with three different leading edges, the open circuit wind tunnel was used. The open circuit wind tunnel breaks down into 5 sections: the settling chamber, where the turbulence from incoming air is removed; the contraction cone, which smoothly accelerates the airflow; the working or test section, which contains straight airflow for the testing; the diffuser, where the airflow is smoothly slowed into the fan; and lastly the fan, which will pull the air through the tunnel.

The airfoil used in this project is the NACA4412 airfoil. This airfoil has a chord length of 0.1m. it also has a hollowed rod which is used to mount the airfoil in the test section of the wind tunnel.



[Figure 4: NACA4412 airfoil]

Another important apparatus is the 3D electronic balancing unit which is used to mount the airfoil into the wind tunnel test section. The airfoil is mounted into the test section by connecting the hollowed rod attached to the airfoil to one rod attached to this apparatus. The airfoil is mounted onto this apparatus because it is easier to adjust the angle of attack to which is desired for the wind tunnel testing.

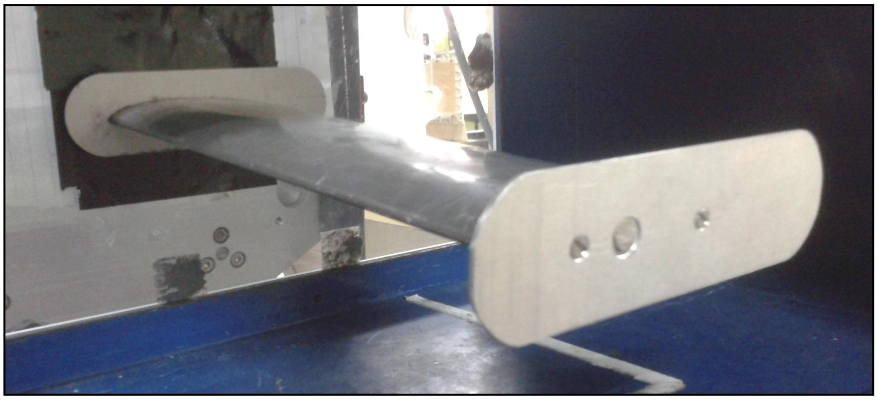


[Figure 5: 3D electronic balancing unit]

The last material used in this wind tunnel test is a couple boxes of modeling clay. The modeling clay was used to make spherical tubercles which was then put onto the leading edge of the NACA4412 airfoil.

## 3.2 Wind Tunnel Test

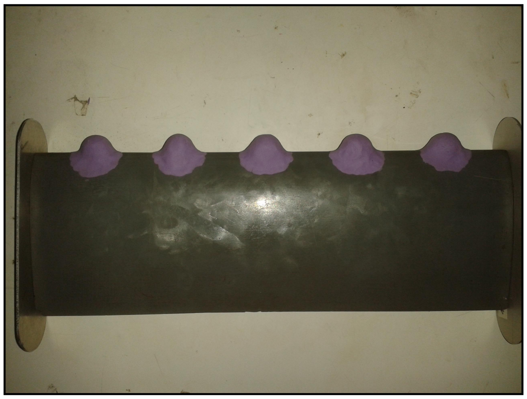
Firstly, the wind tunnel test was performed on the NACA4412 airfoil without the tubercles made of the modeling clay (smooth leading edge). The airfoil was mounted into the test section of the wind tunnel horizontally at 0° angle of attack. The test section was then closed with the clear acrylic covers. The velocity of the airflow in the wind tunnel was set to 10m/s, which is at about Reynold's number of 64,220. The result of the test was obtained from the computer connected to the wind tunnel. The angle of attack of the airfoil was then increased to 2°, 4°, 6° until 20° and the procedures were repeated. Every set of the test was repeated another two times to achieve more accurate results.



[Figure 6: NACA4412 airfoil with smooth leading edge in the test section]

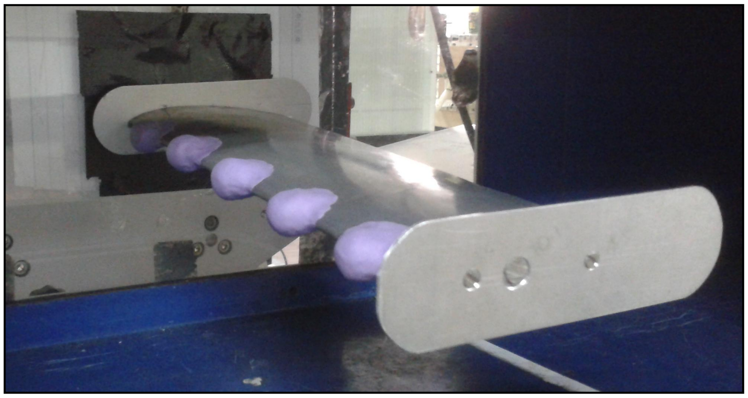
Once the wind tunnel test was finished, the airfoil was returned to 0° angle of attack and the velocity of the airflow was increased to 15m/s, which is about Reynold's number of 96,330. The previous procedures were then repeated for this velocity and the results were obtained. The airflow velocity was again increased to 20m/s with Reynold's number of 128,440 and the procedures were repeated.

After the wind tunnel test was performed on the NACA4412 airfoil with the smooth leading edge, the airfoil was dismounted from the wind tunnel test section. A few spheres made of modeling clay was put on the leading edge of the NACA4412 airfoil which will be the tubercles. These tubercles were set at a distance apart.



[Figure 7: Spherical tubercles at a distance apart on the leading edge]

The airfoil was then mounted into the wind tunnel test. The wind tunnel test was then performed on the NACA4412 airfoil with some tubercles on its leading edge. The test was performed at 10m/s, 15m/s and 20m/s of the airflow velocity. All procedures conducted in wind tunnel performance of the smooth leading edge NACA4412 airfoil were repeated in this test.

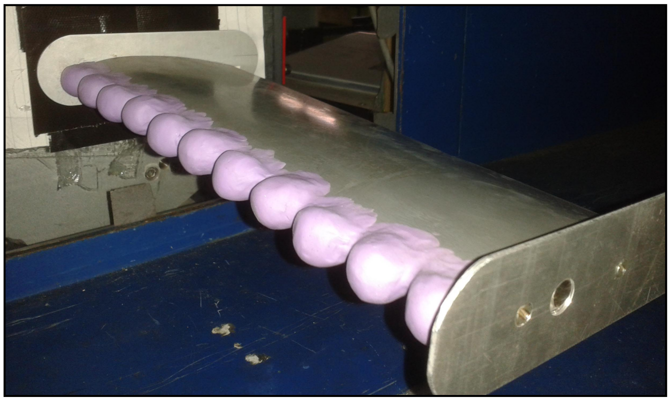


[Figure 8: NACA4412 airfoil with tubercles on leading edge in the wind tunnel test section]

The airfoil was once again dismounted and more spheres were added onto its leading edge.

[Figure 9: Continuous tubercles on the leading edge of NACA4412 airfoil]

The airfoil, which now has more tubercles at a smaller wavelength on its leading edge was then mounted onto the test section of the wind tunnel. All the procedures in the wind tunnel test conducted in the previous experiment were repeated for this airfoil with continuous tubercles on its leading edge.



[Figure 10: Airfoil with continuous tubercles on leading edge mounted in test section]

The results from the wind tunnel test of 3 sets of airfoil with 3 sets of airflow velocity were compared and discussed in Chapter 4.

# CHAPTER 4

# RESULT AND DISCUSSION

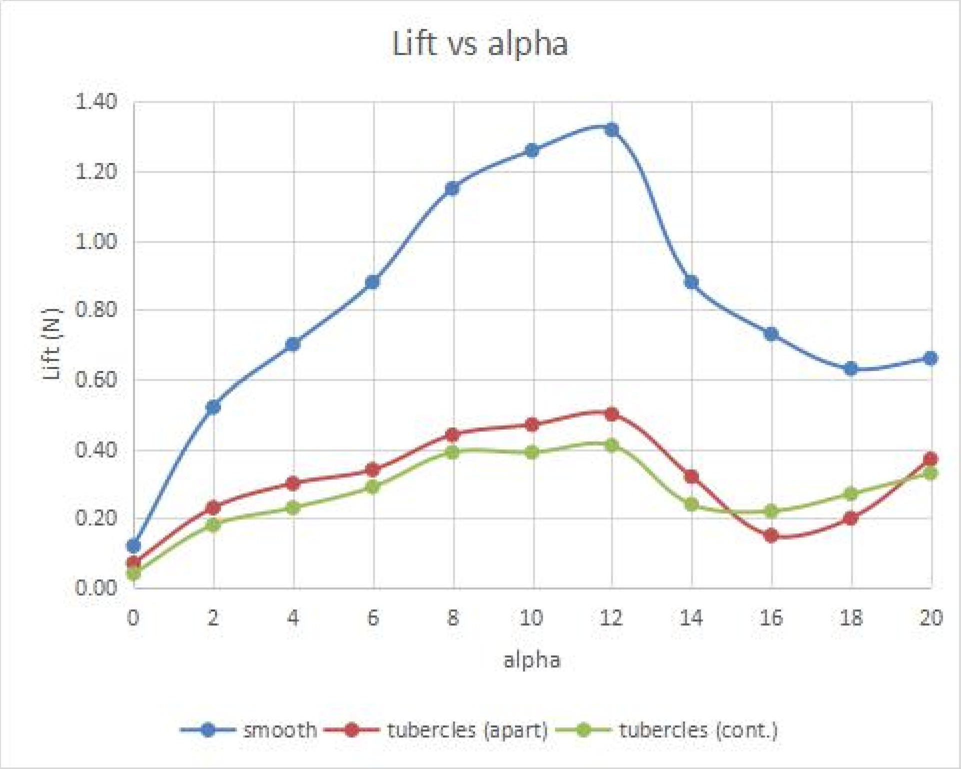
## 4.1 Wind Tunnel Test at Re~64,220

Wind tunnel test was performed on NACA4412 airfoil with three sets of leading edge at the airflow velocity of 10m/s. Below are the results of the test.

| AoA | Smooth Leading Edge | | | Tubercles (apart) on Leading Edge | | | Tubercles (continuous) on Leading Edge | | |
|---|---|---|---|---|---|---|---|---|---|
| | Lift (N) | Drag (N) | CL/CD | Lift (N) | Drag (N) | CL/CD | Lift (N) | Drag (N) | CL/CD |
| 0 | 0.12 | 0.01 | 12.00 | 0.07 | 0.02 | 3.50 | 0.04 | 0.02 | 2.00 |
| 2 | 0.52 | 0.04 | 13.00 | 0.23 | 0.04 | 5.75 | 0.18 | 0.04 | 4.50 |
| 4 | 0.70 | 0.05 | 14.00 | 0.30 | 0.06 | 5.00 | 0.23 | 0.09 | 2.56 |
| 6 | 0.88 | 0.05 | 17.60 | 0.34 | 0.07 | 4.86 | 0.29 | 0.10 | 2.90 |
| 8 | 1.15 | 0.06 | 19.17 | 0.44 | 0.08 | 5.50 | 0.39 | 0.12 | 3.25 |
| 10 | 1.26 | 0.07 | 18.00 | 0.47 | 0.10 | 4.70 | 0.39 | 0.16 | 2.44 |
| 12 | 1.32 | 0.08 | 16.50 | 0.50 | 0.11 | 4.55 | 0.41 | 0.17 | 2.41 |
| 14 | 0.88 | 0.09 | 9.78 | 0.32 | 0.14 | 2.29 | 0.24 | 0.19 | 1.26 |
| 16 | 0.73 | 0.10 | 7.30 | 0.15 | 0.16 | 0.94 | 0.22 | 0.23 | 0.96 |
| 18 | 0.63 | 0.11 | 5.73 | 0.20 | 0.18 | 1.11 | 0.27 | 0.25 | 1.08 |
| 20 | 0.66 | 0.18 | 3.67 | 0.37 | 0.23 | 1.61 | 0.33 | 0.29 | 1.14 |

[Table 1: Results of wind tunnel test for NACA4412 airfoil at Re~64,220]

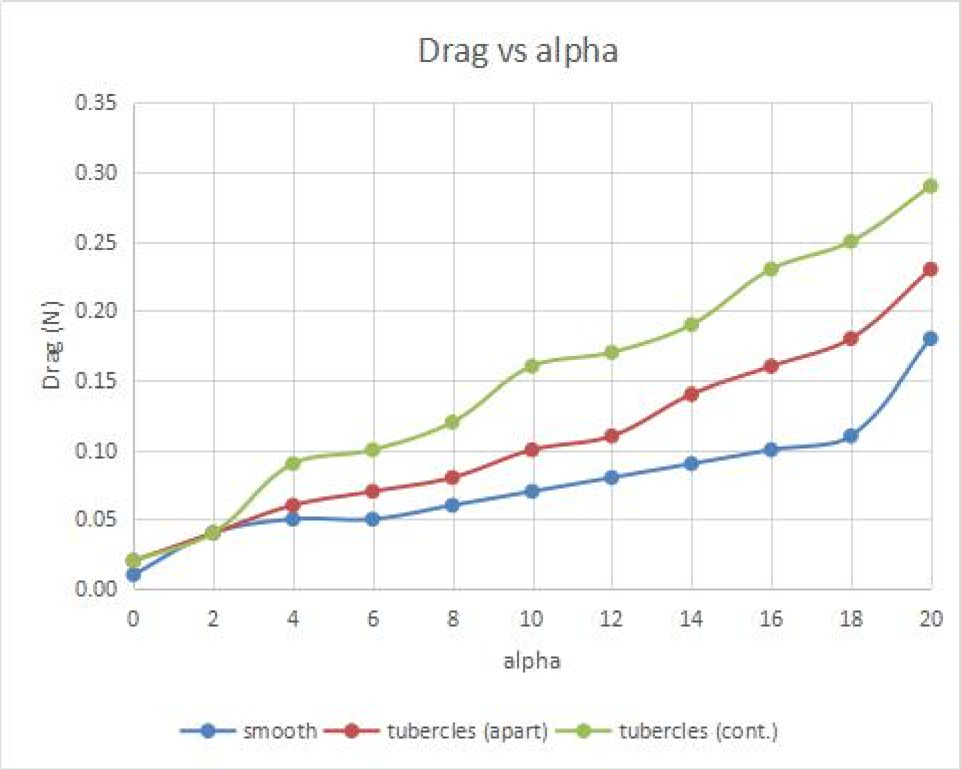
Table 1 shows the values of aerodynamics forces such as lift and drag of the NACA4412 airfoil tested at airflow with Reynold’s number of64,220. The table also shows the difference in results among the 3 different leading edges.



[Figure 11: Graph of lift vs angle of attack at Re~64,220]

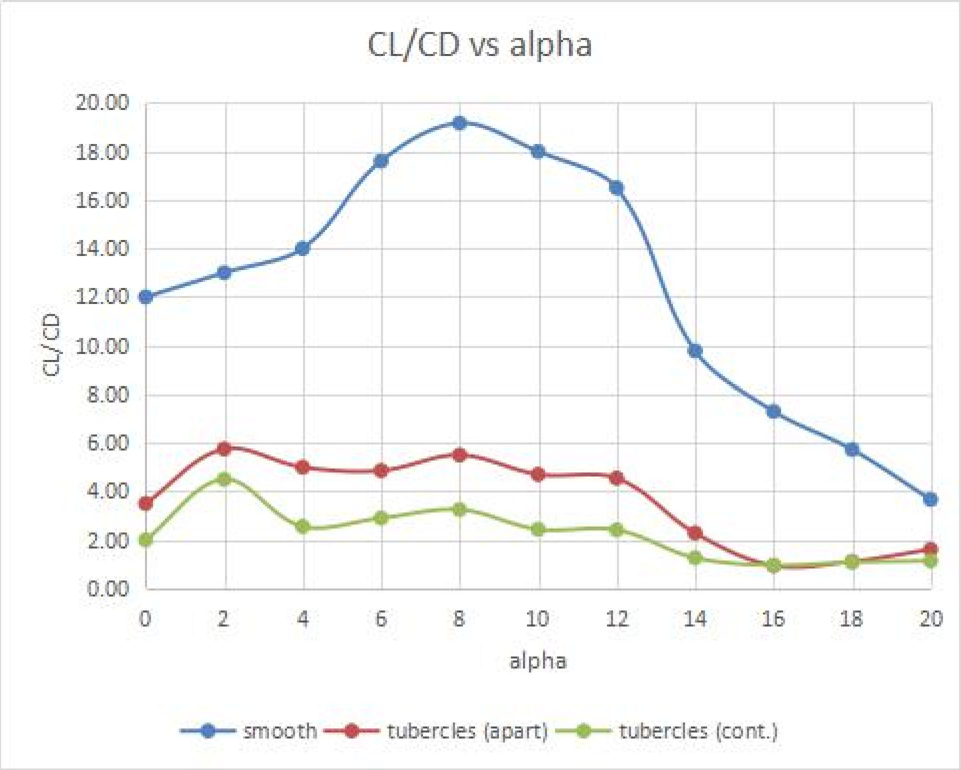
Figure above shows the graph of lift vs angle of attack at Re~64,220. From the graph, it is shown that the airfoil with smooth leading edge produced more lift compared to the airfoils with tubercles on their leading edges. The more tubercles added on the leading edge of NACA4412 airfoil, the lower the lift produced. This is due to the low Reynold's number, where at velocity of 10m/s, the Reynold's number is at about 64,220.

However, the stall produced by both airfoil with tubercles a distance apart on leading edge and airfoil with continuous tubercles on leading edge is less severe compared to the smooth leading edge airfoil.



[Figure 12 Graph of drag vs angle of attact at Re~64,220s]

The graph of drag vs angle of attack of NACA4412 airfoil at Re~64,220 was shown in the figure above. The figure shows that the airfoil with continuous tubercles on its leading edge produced the highest drag force compared to the other two airfoils. It is also shown that airfoil with a smooth leading edge performed with less drag force compared to the ones with tubercles on leading edge. This could be caused that at Reynold's number lower than 300,000, which at v=10m/s the Reynold's number is 64,220, the tubercles on the leading edge act more as extra weights than as vortex generators which reduce the vortices.



[Figure 13: Graph of CL/CD vs angle of attack at Re~64,220]

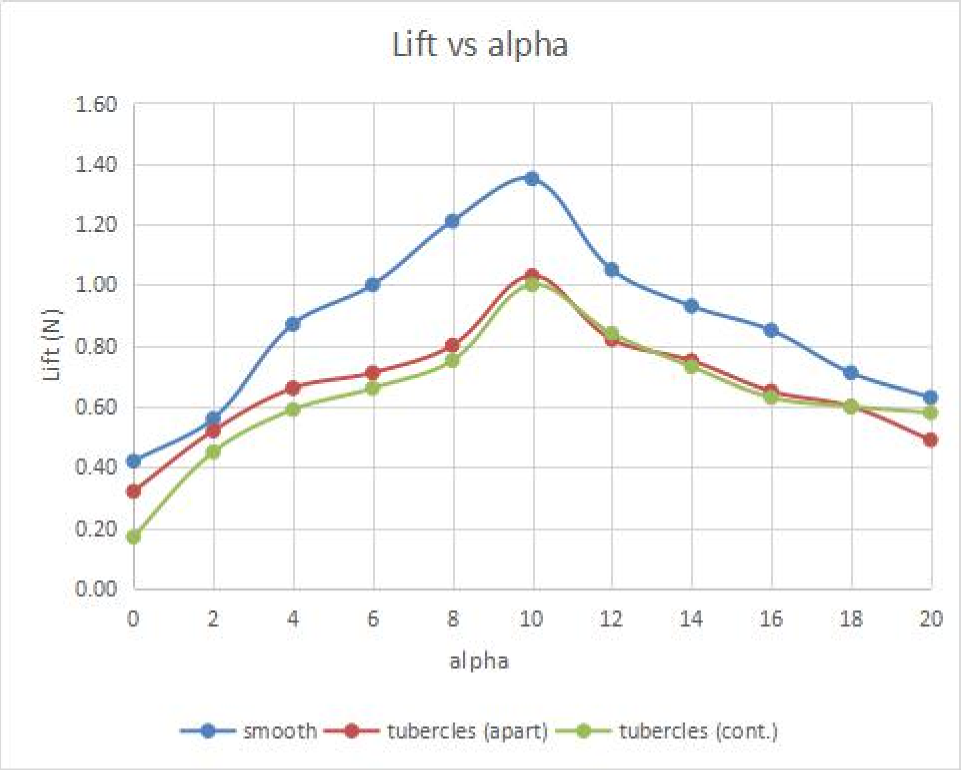
Figure 13 shows the graph of the ratio of lift and drag coefficients against the angle of attack of NACA4412 airfoil at Re~64,220. Just as shown in previous 2 figures, the airfoil with smooth leading edge, which is without tubercles, performed best among all 3 airfoils.

## 4.2 Wind Tunnel Test at Re~96,330

| AoA | Smooth Leading Edge | | | Tubercles (apart) on Leading Edge | | | Tubercles (continuous) on Leading Edge | | |
|---|---|---|---|---|---|---|---|---|---|
| | Lift (N) | Drag (N) | CL/CD | Lift (N) | Drag (N) | CL/CD | Lift (N) | Drag (N) | CL/CD |
| 0 | 0.42 | 0.07 | 6.00 | 0.32 | 0.10 | 3.20 | 0.17 | 0.11 | 1.55 |
| 2 | 0.56 | 0.09 | 6.22 | 0.52 | 0.11 | 4.73 | 0.45 | 0.19 | 2.37 |
| 4 | 0.87 | 0.14 | 6.21 | 0.66 | 0.15 | 4.40 | 0.59 | 0.25 | 2.36 |
| 6 | 1.00 | 0.15 | 6.67 | 0.71 | 0.22 | 3.23 | 0.66 | 0.36 | 1.83 |
| 8 | 1.21 | 0.17 | 7.12 | 0.80 | 0.27 | 2.96 | 0.75 | 0.38 | 1.97 |
| 10 | 1.35 | 0.25 | 5.40 | 1.03 | 0.33 | 3.12 | 1.00 | 0.48 | 2.08 |
| 12 | 1.05 | 0.30 | 3.50 | 0.82 | 0.37 | 2.22 | 0.84 | 0.52 | 1.62 |
| 14 | 0.93 | 0.38 | 2.45 | 0.75 | 0.41 | 1.83 | 0.73 | 0.60 | 1.22 |
| 16 | 0.85 | 0.40 | 2.13 | 0.65 | 0.46 | 1.41 | 0.63 | 0.65 | 0.97 |
| 18 | 0.71 | 0.50 | 1.42 | 0.60 | 0.53 | 1.13 | 0.60 | 0.71 | 0.85 |
| 20 | 0.63 | 0.54 | 1.17 | 0.49 | 0.59 | 0.83 | 0.58 | 0.72 | 0.81 |

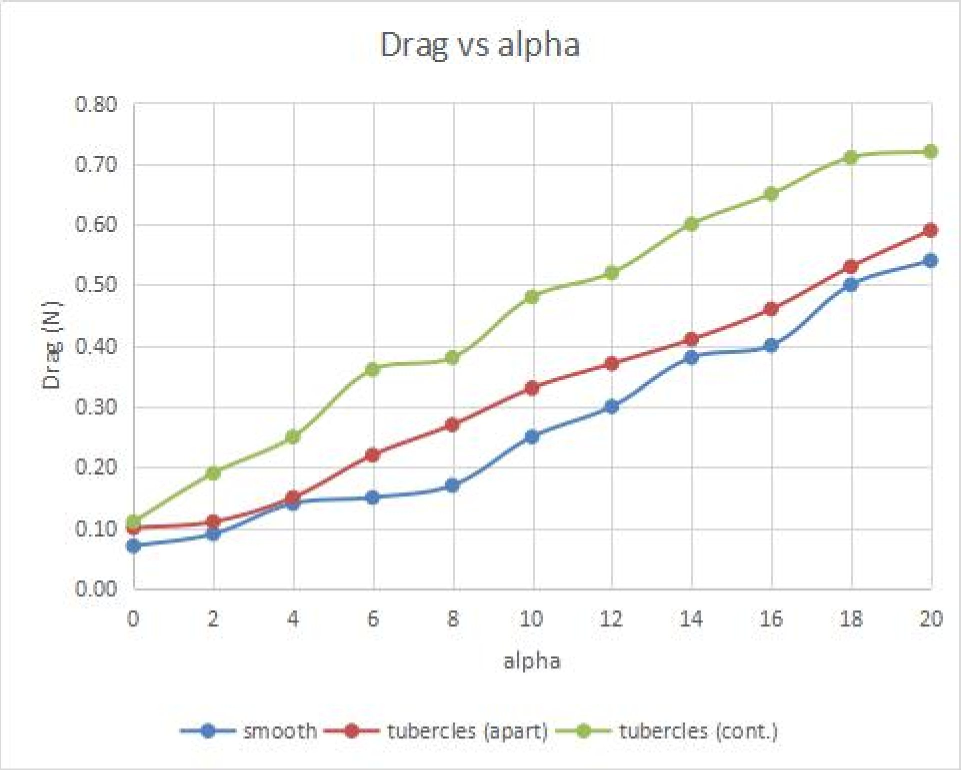
[Table 2: Results of wind tunnel test for NACA4412 airfoil at Re~96,330]

The results of the wind tunnel test performed on NACA4412 with 3 sets of leading edge at the velocity of 15m/s were shown on the Table 2 above. These results are compared in graphs of lift vs angle of attack, drag vs angle of attack as well as the ratio of lift and drag coefficient vs angle of attack in figures below.



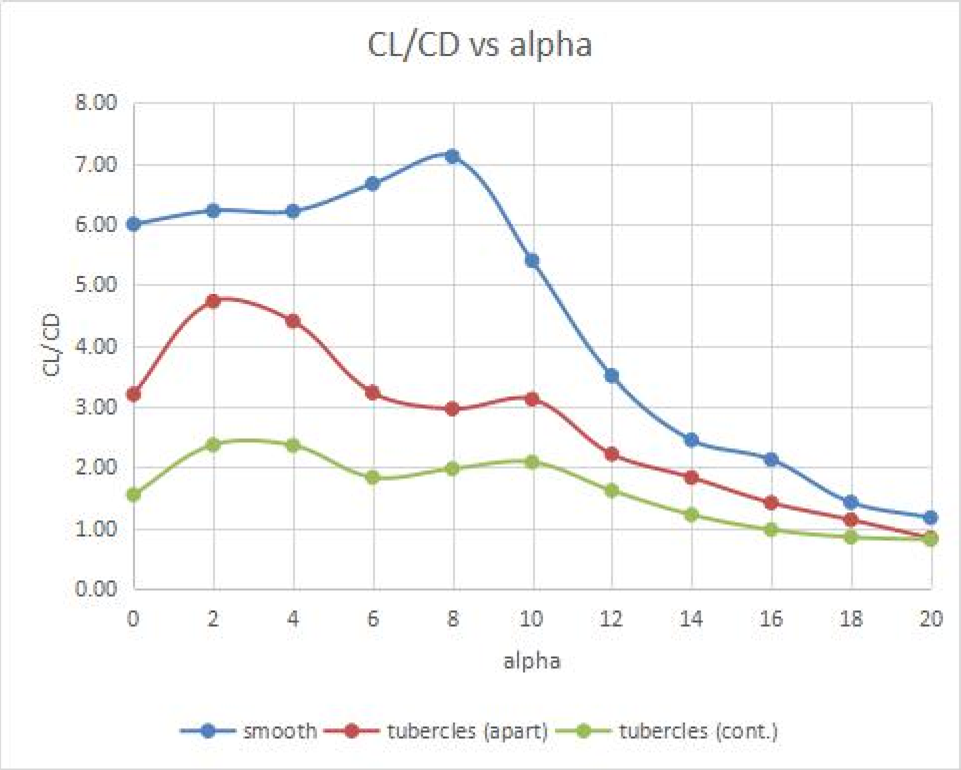
[Figure 14: Graph of lift vs angle of attack at Re~96,330]

Figure 14 shows the graph of lift vs angle of attack of NACA4412 airfoil at airflow velocity of 15m/s. Just like when the test was performed at the velocity of 10m/s, the lift force produced by airfoils with tubercles on their leading edges are less than that of airfoil with smooth leading edge. This is because at velocity of 15m/s, the airflow only has Reynold's number of 96,330. Airfoils with tubercles on leading edges do not perform well at Reynold's number less than 300,000.



[Figure 15: Graph of drag vs angle of attack at Re~96,330]

As shown in figure 15 above, drag force was not reduced when the spherical tubercles made of modeling clay were added along the leading edge of the NACA4412 airfoil. In the graph of drag vs angle of attack above, airfoil with smooth leading edge produced less drag compared to those of airfoils with tubercles on their leading edges. Just like in the test with velocity of 10m/s, the airflow velocity in this test which is 15m/s is too slow for airfoil with tubercles on leading edge to perform well. Instead of reducing drag, the tubercles make the airfoil became heavier.



[Figure 16: Graph of CL/CD vs angle of attack at Re~96,330]

The graph of the ratio of lift and drag coefficient (CL/CD) vs angle of attack of NACA4412 airfoil at velocity of 15m/s in figure 16 above shows that airfoil with smooth leading edge has the best performance, followed by airfoil with tubercles at a distance apart on its leading edge. Airfoil with continuous tubercles on its leading edge has the worst performance out of the 3 sets of airfoil.

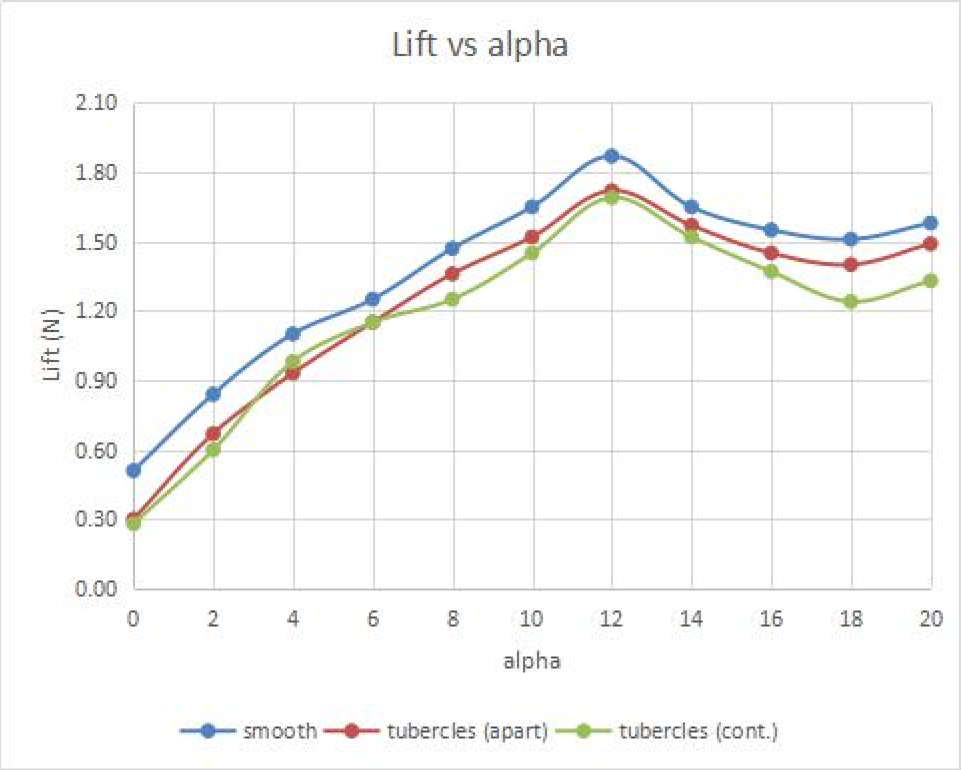
## 4.3 Wind Tunnel Test at Re~128,440

The wind tunnel test was performed on NACA4412 airfoil with 3 sets of leading edge at airflow velocity of 20m/s, which the Reynold's number is 128,440. The results obtained from the wind tunnel test are shown in the table below.

| AoA | Smooth Leading Edge | | | Tubercles (apart) on Leading Edge | | | Tubercles (continuous) on Leading Edge | | |
|---|---|---|---|---|---|---|---|---|---|
| | Lift (N) | Drag (N) | CL/CD | Lift (N) | Drag (N) | CL/CD | Lift (N) | Drag (N) | CL/CD |
| 0 | 0.51 | 0.04 | 12.75 | 0.30 | 0.09 | 3.33 | 0.28 | 0.20 | 1.40 |
| 2 | 0.84 | 0.06 | 14.00 | 0.67 | 0.15 | 4.47 | 0.60 | 0.24 | 2.50 |
| 4 | 1.10 | 0.10 | 11.00 | 0.93 | 0.28 | 3.32 | 0.98 | 0.37 | 2.65 |
| 6 | 1.25 | 0.14 | 8.93 | 1.15 | 0.37 | 3.11 | 1.15 | 0.49 | 2.35 |
| 8 | 1.47 | 0.16 | 9.19 | 1.36 | 0.49 | 2.78 | 1.25 | 0.57 | 2.19 |
| 10 | 1.65 | 0.21 | 7.86 | 1.52 | 0.55 | 2.76 | 1.45 | 0.66 | 2.20 |
| 12 | 1.87 | 0.29 | 6.45 | 1.72 | 0.61 | 2.82 | 1.69 | 0.72 | 2.35 |
| 14 | 1.65 | 0.42 | 3.93 | 1.57 | 0.73 | 2.15 | 1.52 | 0.81 | 1.88 |
| 16 | 1.55 | 0.54 | 2.87 | 1.45 | 0.86 | 1.69 | 1.37 | 0.93 | 1.47 |
| 18 | 1.51 | 0.67 | 2.25 | 1.40 | 0.97 | 1.44 | 1.24 | 0.98 | 1.27 |
| 20 | 1.58 | 0.70 | 2.26 | 1.49 | 1.00 | 1.49 | 1.33 | 1.06 | 1.25 |

[Table 3: Results of wind tunnel test for NACA4412 airfoil at Re~128,440]

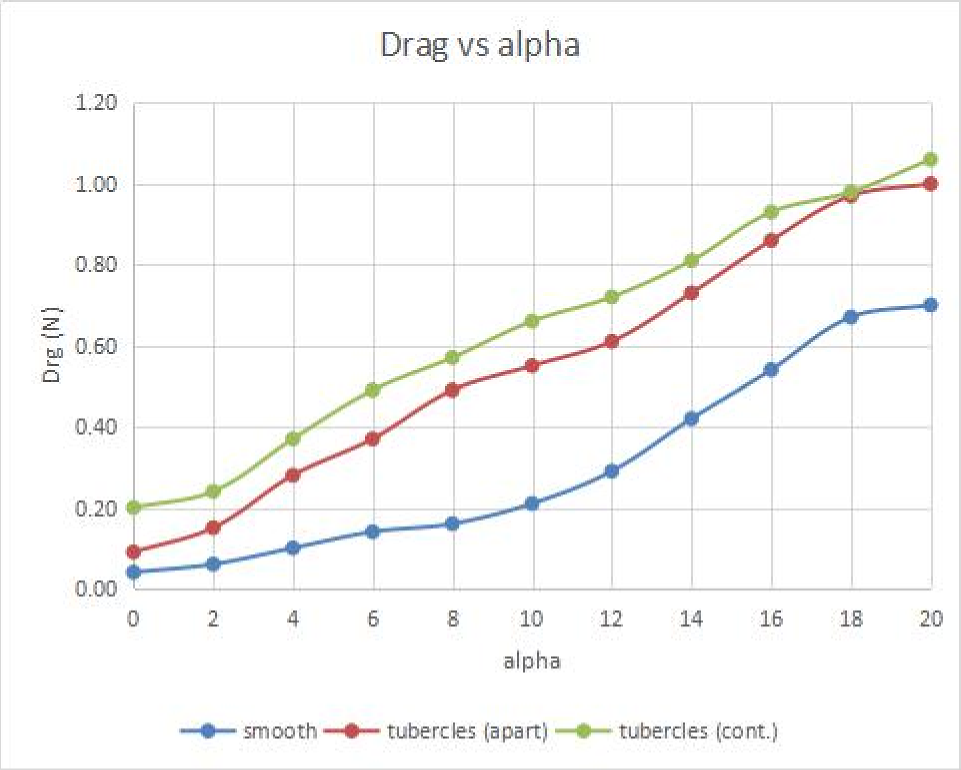
The results from Table 3 above were compared in 3 graphs which are graph of lift vs angle of attack, graph of drag vs angle of attack as well as graph of ratio of lift and drag coefficients (CL/CD) vs angle of attack.



[Figure 17: Graph of lift vs angle of attack at Re~128,440]

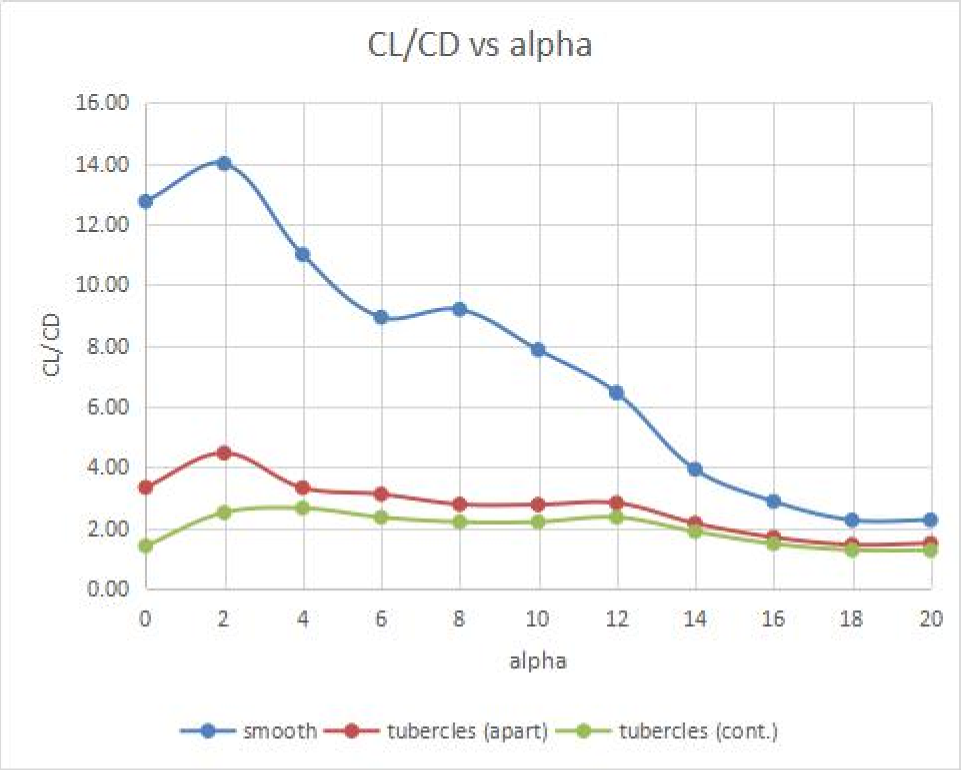
Compared to previous graphs of lift vs angle of attack at velocities of 10m/s and 15m/s, the graph in figure 17 shows that lift force produced by 3 sets of airfoil are almost similar. However, NACA4412 airfoil with a smooth leading edge still produced better lift force compared to the other two airfoils.

Still, the almost similarity of the lift profiles shows that the higher the velocity, the better the performance of airfoil with tubercles on its leading edge.



[Figure 18: Graph of drag vs angle of attack at Re~128,440]

Graph of drag vs angle of attack of the NACA4412 airfoil at airflow velocity of 20m/s is shown in figure 18 above. As per usual, the airfoil with smooth leading edge produced less drag compared to the other two airfoils. Just like in wind tunnel test at velocities of 10m/s and 15m/s, the velocity of 20m/s is still too low to ensure the tubercles on leading edge of an airfoil help reducing penalty drag of the airfoil.



[Figure 19: Graph of CL/CD vs angle of attack at Re~128,440]

In the graph of CL/CD vs angle of attack at v=20m/s shown in figure 19, the low velocity with low Reynold's number (less than 300,000) contributes to the poor performance of NACA4412 airfoil with tubercles at a distance apart on its leading edge as well as that of airfoil with continuous tubercles on its leading edge.