A Study of Impacts of Airfoil Geometry on the Aerodynamic Performance at Low Reynolds Number

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***Abstract*—The aerodynamic performance of airfoils has been studied in several studies; however, the performance is highly relying on the airfoil geometry and the flow characteristics such as the flow type (laminar or turbulent) and Reynolds number. This paper focuses on understanding the aerodynamic performance of airfoils in a low-speed environment (low Reynolds number) versus the airfoil geometry. This paper would be a guide to the airfoil design and optimization processes toward the design target under similar flow conditions. Therefore, several parameters of the airfoil geometry, such as maximum thickness, maximum camber, their location, and reflex angle were studied in a low Reynolds number range from 0.3×10^6 to 0.8×10^6. Three airfoil parameterizations, NACA 4-digit, PARSEC, and Bezier curve, were utilised to generate the airfoil coordinates for different studied parameters. A two-dimensional aerodynamic solver, XFOIL, was used to evaluate the aerodynamic performance of the airfoils. The results show that varying the airfoil geometry results in a noticeable change in the lift, drag, and moment coefficients. Also, as expected, increasing the Reynolds number has resulted in a good performance.**

***Keywords*—airfoil, low reynolds number, airfoil shape**

I. INTRODUCTION

Low Reynolds number environment widely exists in real industry life. Such operating an aircraft or any lifting body at a low Reynolds number will make the viscous effect more dominant [1, 2]. The wing sections are usually designed to achieve the desired aerodynamic performance in a specific environment. The shape of an airfoil can be manipulated to overcome or reduce the impact of a low Reynolds number on the performance [3, 4]. At low Reynolds numbers, the rapid separation in the boundary layer will affect the aerodynamic performance of airfoils [5]. This leads to an unsteady behavior and therefore a fluctuation in the resulting moment and force with time [6]. Furthermore, the separation bubble will initiate the transition from laminar to turbulent flow [6, 7], see Fig. 1-A. The airfoil shape is definitely having influence on the location of the separation and its intensity along the upper and lower surface of the wing section. Moreover, the Reynolds number and the angle of attack also have this influence on the aerodynamic performance of the airfoils but this also could be mitigated or manipulated along with the airfoil shape [8]. The reduction in the gradient of the lift-curve and the increase in the drag-curve are obviously noticed when separation is happened [9]. A large amount of air resistance can be generated from the pressure drag at the laminar flow region when the laminar separation bubble is taken place. After the laminar separation bubble, the flow attempts to reattach to the wing and turn into turbulent flow or could remain separated. In case the flow remains separated, the lift force will abruptly decrease with a remarkable rise in the drag force. The surface roughness of an airfoil has an effect on the performance such as decreasing the lift/drag ratio when the Reynolds number at approximately more than 105. Nevertheless, below this Re, roughness can be beneficial due to the discontinuity in the surface, which can participate to forming the flow separation [10].

Reynolds number of the flow has a noticeable effect on the performance and this effect can be recognized or mitigated by changing the airfoil shape. The most impact of flying under low Reynolds number is the increase in the viscous drag and it becomes clear when separation occurs. The airfoil shape can be modified through an optimisation procedure to reach an optimal design that can perform well without any separation within certain range of angle of attack. So, the need is raised to understand how the airfoil shape parameter can affect the performance and how the Reynolds number plays its roll in that. Therefore, for a range of Reynolds number, this study will focus on the effect of the various airfoil shape parameter on the airfoil performance. The Reynolds number range chosen for this study, is from 0.3×10^6 to 0.8×10^6.

There are several equations can generate airfoil coordinates, however, not all these equations can deal with all airfoil shape parameters targeted in the study. Therefore, a combination of airfoil parameterizations is used to generate airfoil coordinates for different airfoil parameters. Table I shows the main parameters of airfoil that can be altered for three different parametrization equations. The mathematical equations of these parametrization methods are detailed in the following

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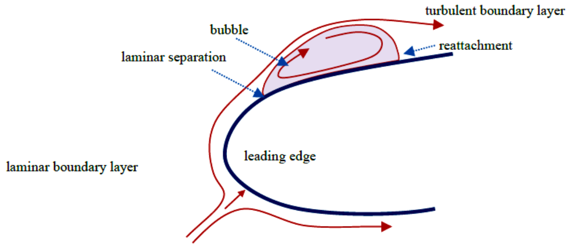
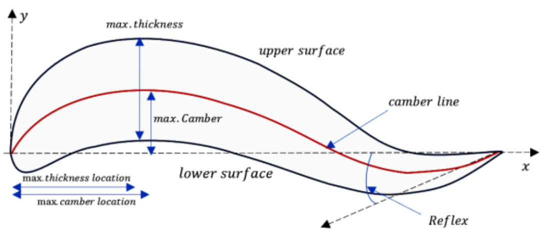
references [8, 11–14] and will not be detailed in this paper. Some parameters can be directly assigned in the parametrization equations. Furthermore, the other parameters are generated as a result of other parameters depending on the nature of the parametrization equations. This problem has been studied in several research papers which came up with using a combination of parametrizations used together to signify certain parameters, see the references [15, 16].

As the study will examine several airfoil geometries at several flow characteristics and several angles of attack, a two-dimensional aerodynamic solver (XFOIL) has been utilised to evaluate the aerodynamic performance. It utilizes a combination of inviscid-viscous flow analyses to converge with a result which can be in a good agreement with experimental results [17]. Therefore, XFOIL has been used in many optimization processes and studies due to its good and rapid results [18–20]. However, the pitching moments calculated by XFOIL is disputed by present work by the authors and some others such as by Selig *et al.* [21], especially for symmetric airfoils at low Reynolds numbers. However, the pitching moment of asymmetric airfoils can be accepted if an experimental validation was conducted afterwards.



(A). Structure of laminar separation bubble



(B). Airfoil Shape Parameters

Figure 1. Structure of laminar separation bubble and Airfoil Shape Parameters.

TABLE I. AIRFOIL SHAPE PARAMETERS

Parameters	NACA 4-digit	PARSEC	Bezier
Maximum camber	*	*	***
Position of Maximum camber	*	*	***
Maximum Thickness	*	*	***
Position of Maximum Thickness	**	*	***
Reflex angle	**	*	***
Thickness distribution	****	****	***

* Yes: can be modified directly
**No: cannot be modified directly
***Can be modified explicitly (no direct change available
****Highly restricted by other parameters

II. THE GEOMETRIC PARAMETERS

In order to study the effect of the wing section geometry on the aerodynamic performance, three geometry equations (NACA 4-digit, PARSEC and Bezier parametrization) are used to generate the airfoil coordinates. In each case, only one parameter is studied under the range of the Reynolds number 0.3×10^6 to 0.8×10^6.

A. Effect of the Maximum Thickness Ratio

The NACA 4-digit coordinates generator has been used to reach airfoil coordinates with different maximum thickness ratios. Symmetric airfoils are taken for this part of study. For example, when thickness ratio of 15% was taken, the airfoil shape was NACA0015 and so on. At different airfoil thickness ratio, the aerodynamic performance is investigated as shown in Fig. 2.

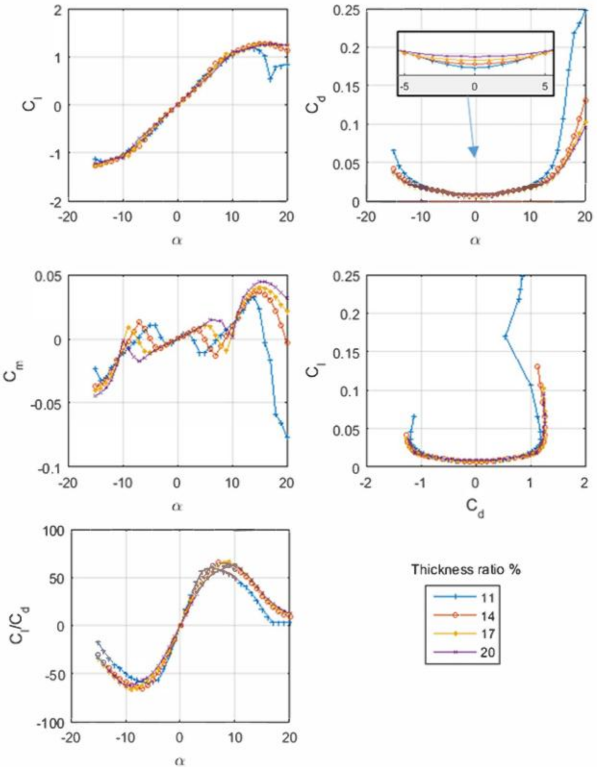


Figure 2. Effect of maximum thickness ratio on aerodynamic performance Re=0.5×10^6.

The influence can be summarized as the following:

- Up to approximately 16%, it is found that increasing the thickness ratio can enhance the maximum lift and the ratio of the maximum lift /drag. However, the trend is reversed when the thickness ratios become higher than 16%. The later behavior occurs because of the high drag generated as the increase in the thickness can lead to a laminar separation.
- Increasing the thickness ratio leads to an increase in the angle of attack, which corresponds to the maximum lift/drag ratio.
- Increasing thickness ratio can increase the drag at a given angle of attack up to about 6 degrees. After 6 degrees, the behavior is reversed.

- The pitching moment results show a suspicious behavior against the angle of attack, particularly with thicker airfoils. Since these airfoils are symmetric, the pitching moment should be very small and constant about the quarter-chord before the separation region. However, this is because XFOIL might predict laminar separation that may not have existed in real flow.
- Increasing Reynolds number can enhance the aerodynamic performance (see Fig. 3). At higher Reynolds numbers, the viscous effect is reduced, so the drag force is reduced.

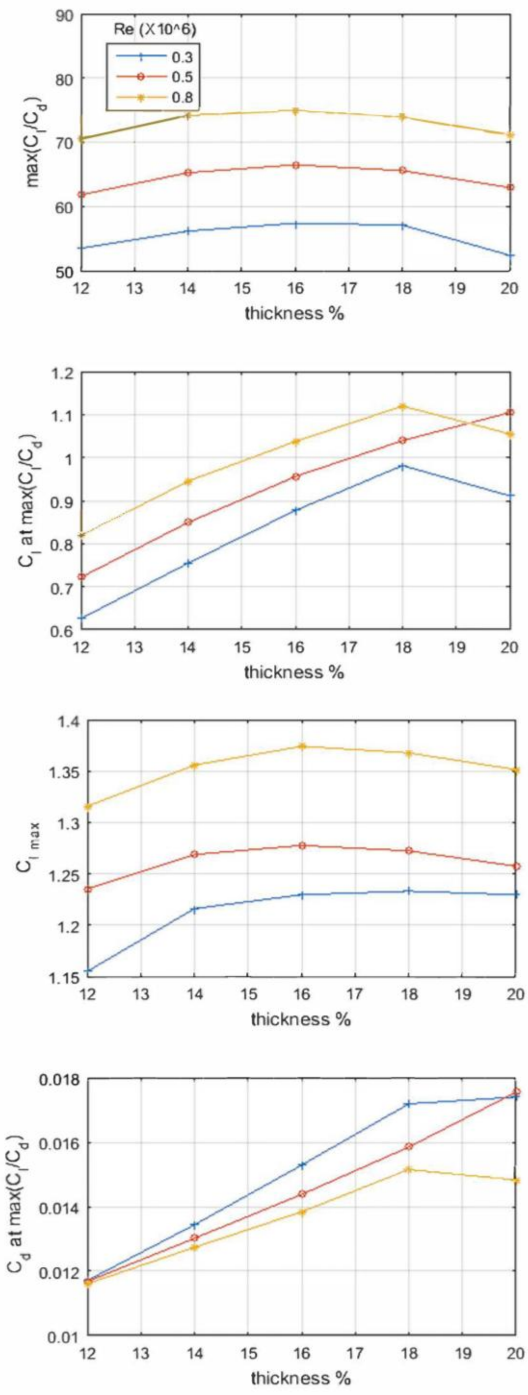


Figure 3. Effect of Reynolds number and maximum thickness on the aerodynamic performance.

B. Effect of the Position of the Maximum Thickness

The NACA 4-digit generator equation does not offer an ability to change the location of the maximum thickness ratio. Therefore, Bezier-curve parametrization has been used to generate symmetrical airfoils with a maximum thickness 12%, but at different locations.

The position of the maximum thickness ratio obviously has an influence on the aerodynamic performance as depicted in Figs. 4 & 5. Shifting the position of the maximum thickness ratio towards the trailing edge can reduce the maximum lift in addition to reducing the pitching moment and drag corresponding to the maximum lift/drag ratio. The lift and drag reduced with shifting the location of the maximum thickness towards the trailing edge. With the studied location range, it is likely that the area of laminar flow becomes larger which in turn result in a reduction in the drag coefficient. However, at low Reynolds numbers, laminar separation becomes dominant and has led to a reduction in the lift and an increase in the drag. Therefore, when increasing the Reynolds number to 0.8 million, the drag lift behave reversibly. The pitching moment will be affected because the lift and drag forces will be differed when shifting the maximum thickness location since the moment was calculated at 0.25 of the chord in all cases.

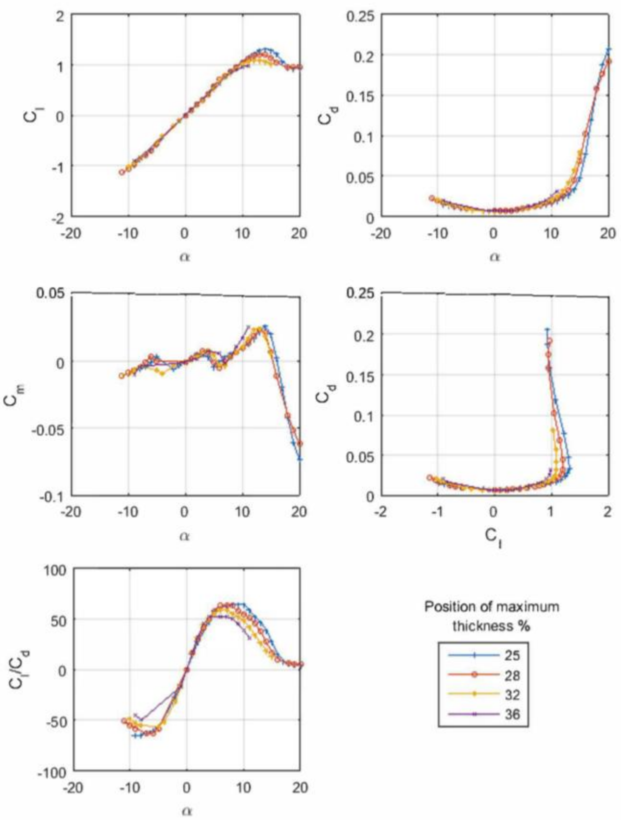


Figure 4. Effect of location maximum thickness on the aerodynamic performance, maximum thickness=12%, Re=0.5×10^{6}.

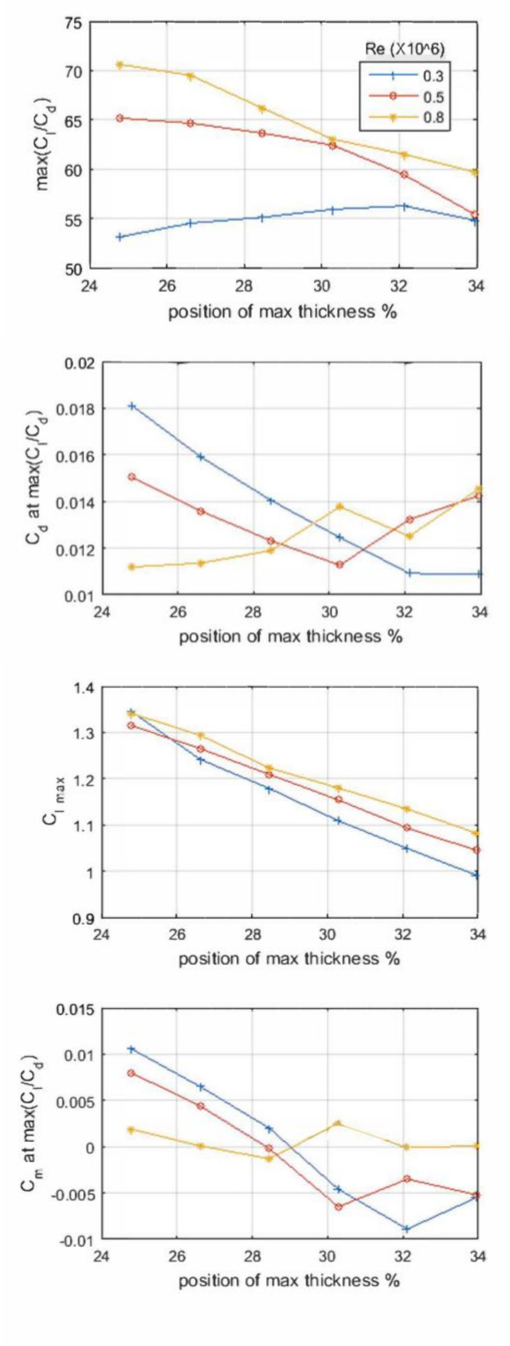


Figure 5. Effect of Reynolds number and location of the maximum thickness at maximum lift/drag ratio.

C. Camber Ratio (Max Camber) and its location

The NACA 4-digit formula has been facilitated to create airfoils to be studied with several camber-ratio (maximum camber) and their location. As expected, and shown in Figs. 6 &7, increasing the camber ratio has a pronounced influence on the aerodynamic performance such as increasing the maximum lift, zero lift angle of attack, lift/drag ratio and pitching moment in addition to a decrease in drag. However, for this case study, an increase in drag is shown after 2% camber ratio.

Figs. 8 & 9 show the effect of the maximum camber position on the aerodynamic performance. Shifting the position of the maximum camber towards the trailing edge can decrease drag, pitching moment and lift corresponding to the maximum lift/drag ratio. The maximum lift/drag ratio can be increased but with a limit of maximum camber location.

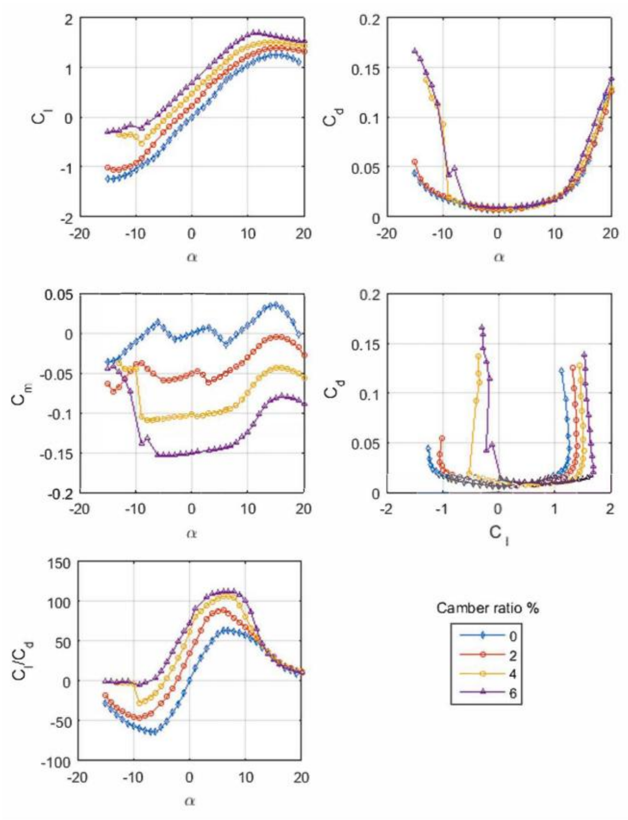
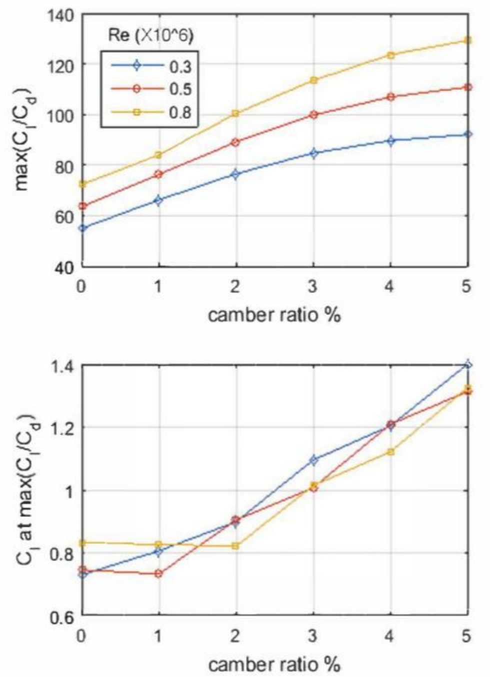


Figure 6. Effect of camber ratio on aerodynamic performance. max thickness 13%, camber location at 40%, at Re=0.5×10^{6}.



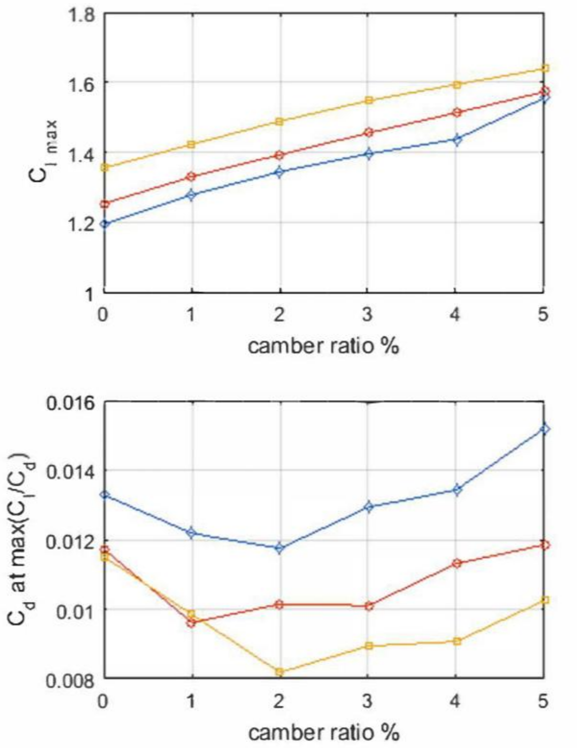


Figure 7. Effect of Reynolds number and camber ratio at maximum lift/drag ratio, max thickness 13%.

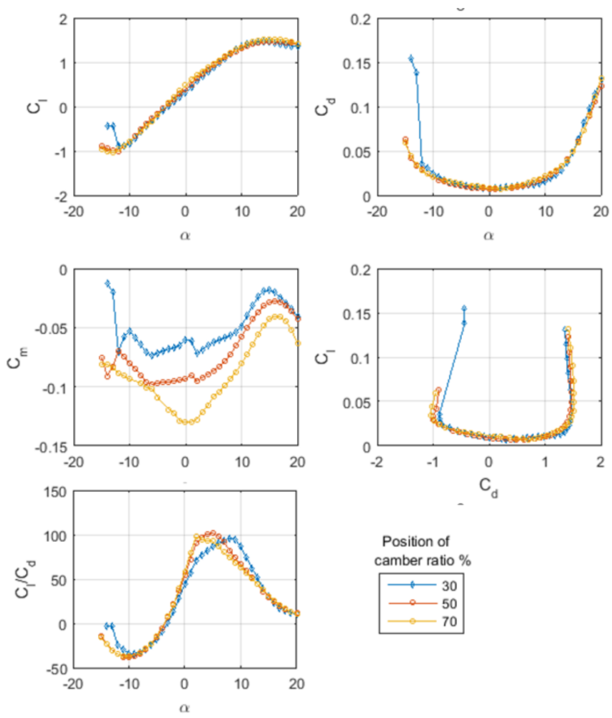


Figure 8. Effect of Reynolds number and Camber position at maximum lift/drag ratio, Max thickness 13%.

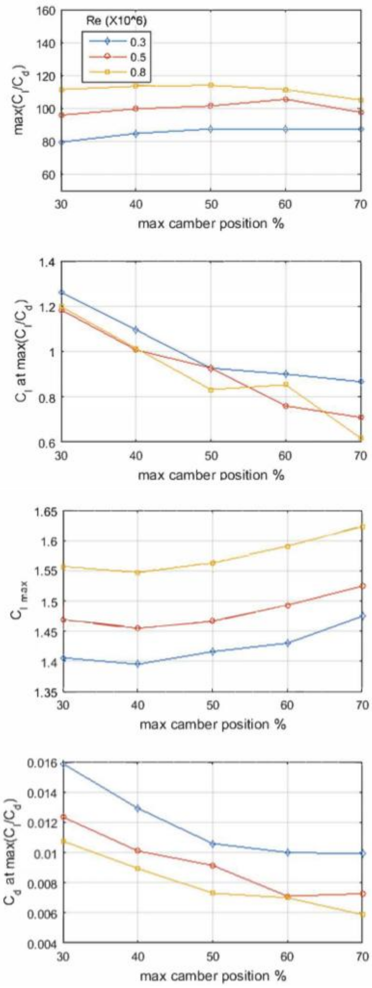


Figure 9. Effect of Reynolds number and camber position at maximum lift/drag ratio, max thickness 13%.

III. Reflex Camber

The reflex of trailing edge is used in many airfoils especially with flying wing sections where a small pitching moment is desired. A combination of two airfoil parametrizations has been adopted, Bezier-curve for the thickness distribution and PARSEC parametrization for the camber line. The reason for using PARSEC parametrization is its ability to bend the trailing edge with several angles (reflex angle). Fig. 10 shows the samples of reflex followed in this study.

An airfoil with 12% maximum thickness and 5% camber is selected. Figs. 11& 12 show the effect of reflex angle on the aerodynamic performance. These effects can be summarized as follows:

- As the reflex angle increases, the lift is reduced and the drag increases. However, at angle of attack of about 12 degrees, the reflex angle shows slight influence which apparently happens at the separation angle of attack.

- As expected, the moment shows high sensitivity to changing the reflex angle. A positive moment can be achieved with a high reflex angle as the amount of the lift at the lower surface near the trailing edge (near the reflex) can produce a positive moment.
- The lift to drag ratio is reduced as the reflex increases. This is mainly due to the high reduction in the lift as shown in Fig. 12.
- As in the other cases, increasing the Reynolds number will enhance the aerodynamic performance. However, the main issue here is that the maximum lift coefficient is highly affected by reflex angle than by the Reynolds number because the lift force on the lower surface near the camber (opposite lift) increases with increasing Reynolds number and has led to a reduction in the net lift force.

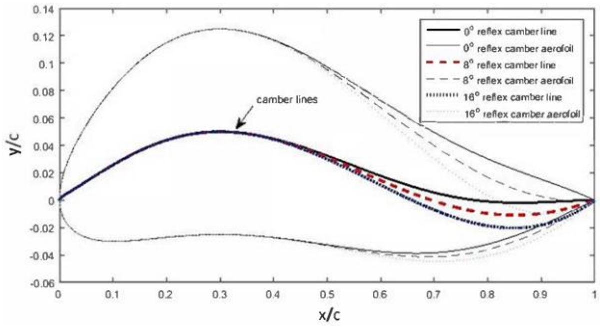


Figure 10. An Airfoil Shape with Several Reflex Angles.

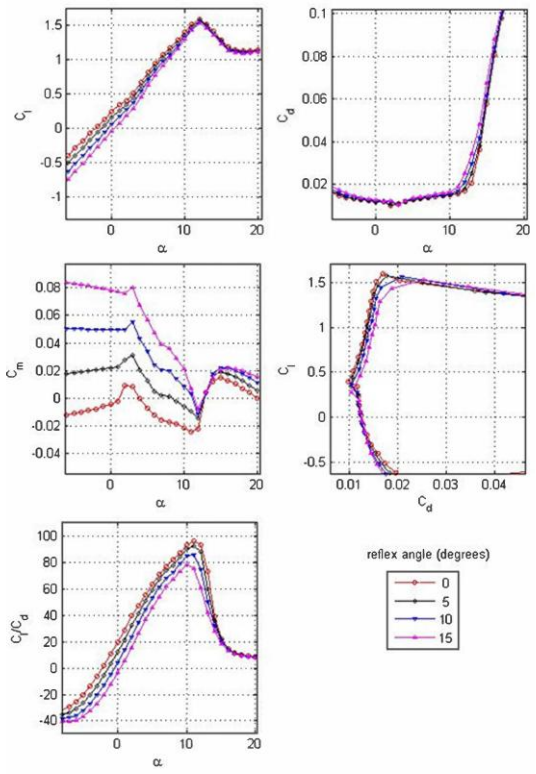


Figure 11. Effect of Camber Ratio Position on Aerodynamic Performance. Re=0.5×10^6, Max thickness 12%, camber ratio 5%.

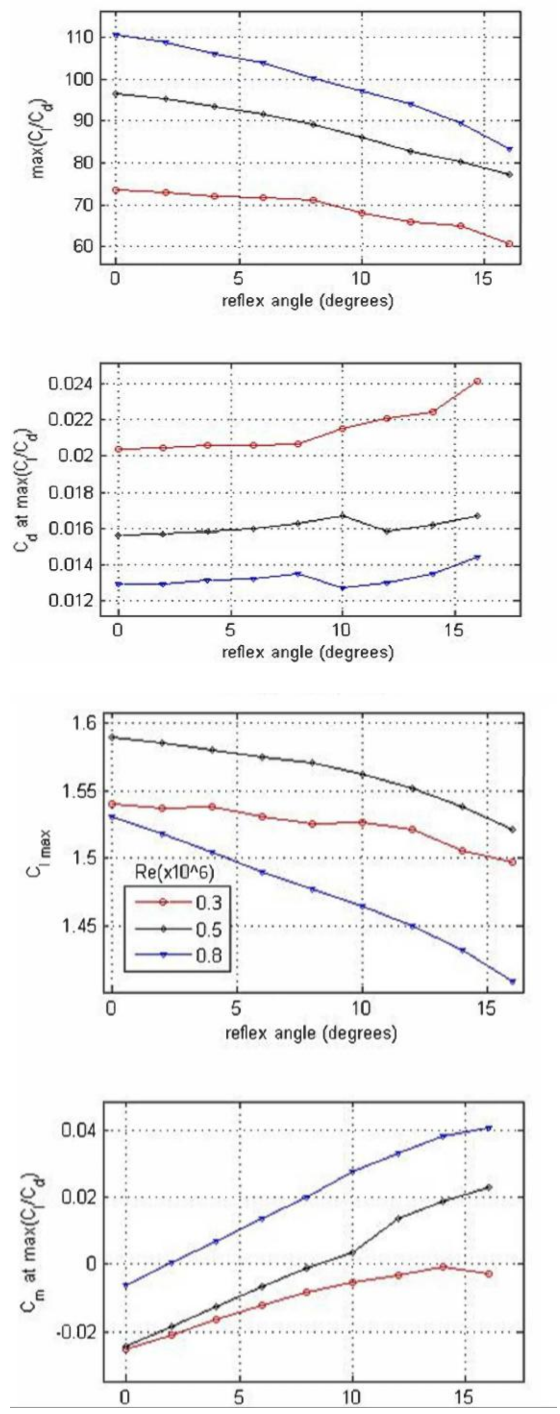


Figure 12. Effect of Reynolds number and Reflex Angle at maximum lift/drag ratio. Max thickness 12%, camber ratio 5%.

IV. CFD Validation

In this paper, several airfoil geometries at varies angles of attack and Reynolds numbers have been studied using a low fidelity software Xfoil. A CFD analysis has been conducted to validate some results using Ansys Fluent. A low Reynolds number turbulent model; SST; has been used to validate the results achieved for three airfoils; NACA0009, NACA0012 and NACA0018 at Re=0.5x10^6 as indicated in Fig. 13.

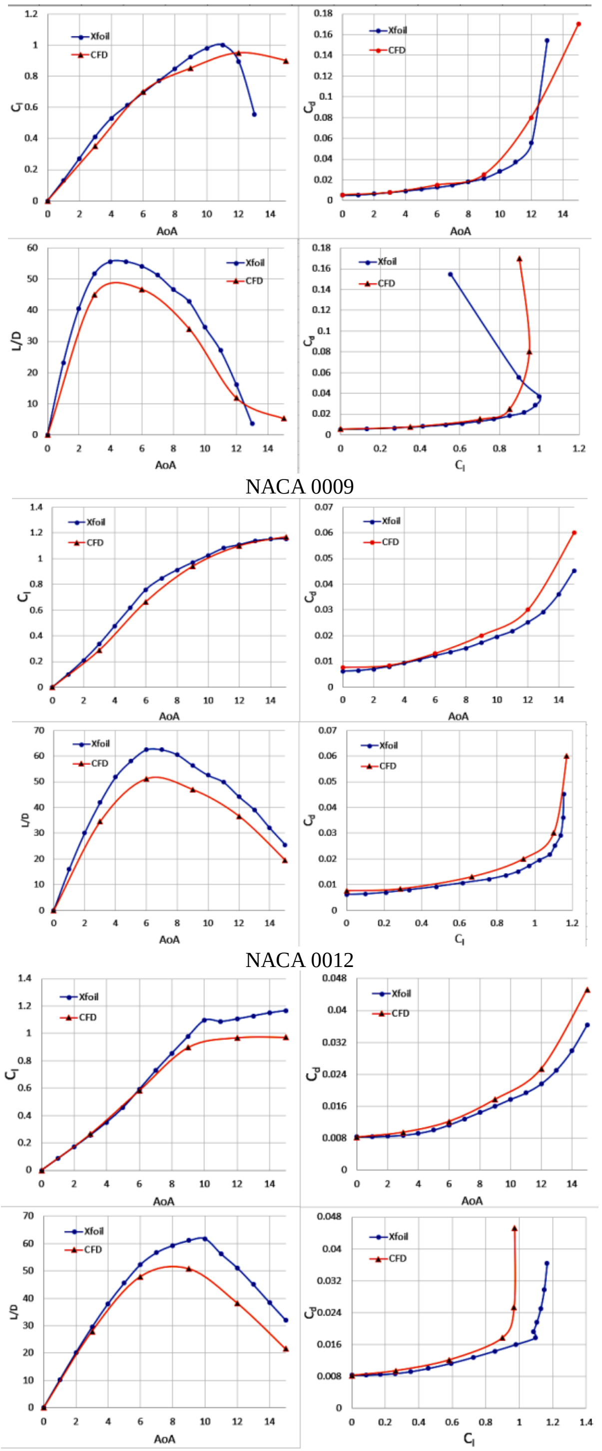


Figure 13. A comparison between Xfoil and ANSYS Fluent results. Re=0.5×10^6.

The validation result demonstrations that Xfoil can predict the lift and drag very well at lower angles of attack. But, at higher angles of attack, due the viscose drag, the results of Xfoil deviate from that of CFD results. However, if the results were compared with that in Fig. 3, the influence of the maximum airfoil thickness still the same. This indicates that the aerodynamic behavior, studied in this paper using Xfoil, is reliable if compared with the CFD results.

V. Conclusion

Several parameters of airfoil geometry, such as maximum thickness, maximum camber, their location, and reflex angle have been studied under a range of low Reynolds number values from 0.3×10^6 to 0.8×10^6. Three airfoil parameterizations, NACA 4-digit, PARSEC and Bezier curve, were utilised to generate the airfoils coordinates for various studied parameters. The results show that Reynolds number has a significant impact on the aerodynamic performance as the low Reynolds number operation can lead to a lower aerodynamic performance due to the high drag force created by laminar separations and then reduces the lift forces. The aerodynamic performance can be improved over a certain range of airfoil thickness and depends on the operating Reynolds number. The location of the maximum thickness demonstrates influences on the lift to drag ratio and the maximum lift coefficient in addition to the pitching moment. Reflex angle can be adjusted to achieve higher lift and drag coefficient in addition to producing a positive pitching moment.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ahmad Alsahlani carried out the aerodynamic solver results and the CFD Validation. Mohammed Al-SAAD's contribution was to emblement the comparison and discus the results. Mohammed Al- Mosallam carried out the check and proofreading in addition to contribute in the CFD analysis. All the Authors read and approved the final manuscript.

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