Experimental Study on Enhancing the Lift Coefficient of NACA0015 Airfoil by Trapping Vortices

Wanis Mustafa Edukali Shibani*, Ibrahim A Ibrahim Swidan*, Muhsen A Mansour Abdusalam**

*HIGHER INSTITUTE OF SCIENCE AND TECHNOLOGY MESALLATA

**FACULTY OF TECHNICAL ENGINEERING MESALLATA

Corresponding author; Wanis Mustafa Edukali Shibani
Email addresses: wanismustafa@yahoo.com

Key words: Airfoils; wind tunnel; Experiments

1. Abstract

This paper summarized the aim to investigate the possibility of trap vortex to improve Coefficient of Lift C_L for aircraft wing. Experimental study had been conducted in aerodynamic lab in open loop low speed wind tunnel (OLLS), for the case of two and three dimensions. The experiments were conducted for both smooth and grooves airfoils. The grooves meant to trap the vortex. The pressure at points on the top and bottom surfaces were measured at the angle of attack of 20, 25, 30, 35 and 40 degrees at the speeds of 15, 20 and 25 m/sec and Reynolds number varied from 131761 to 220332. The calculated C_L was plotted against α for every speed, the graphs of C_L verses α for the smooth airfoil were compared to the published data, they were in good agreement, and this justified the validity of the method used and results obtained. The C_L for the airfoils with one and two grooves were then plotted against the angle of attack for the various velocities. The graphs obtained showed that airfoil with grooves produced better C_L values. The two grooves having highest C_L values 1.18, i.e., with an increment of 10.45% compared to the plain aerofoil. This shows that the aim of this paper to increase C_L values through trap vortex methods has been successfully justified.

2. Introduction

The idea of trapping a vortex is old, and it is not easy to find out who first suggested it Ringleb (1961). A trapped vortex could be just a steady separation eddy above an airfoil at high angle of attack, but the use of a vortex cell helps. Practical implementation of the trapped-vortex idea is tricky, since the trapped vortex needs to be almost steady in the sense that it should remain in the close vicinity of the body. The first successful use of a trapped vortex in a flight experiment was claimed by Kasper (1975) in the seventies with is well known wing.

Tip vortices are generated at the tip of lifting surfaces where fluid flows from the high-pressure side to the low-pressure side, then rolls up and travels to the blade wake. The tip vortex system originated from the complex three-dimensional separated flow is highly unsteady and turbulent. The interactions between the primary and the secondary vortices, the vortices and the separated shear layer, and the vortices and the wakes occur simultaneously in the flow field.

The wing tip vortex is of importance because of its effects on many practical problems such as the landing distances for aircraft, the blade/vortex interactions on helicopter blades, propeller cavitation's on ships, and other fields. For example, tip vortices contribute to the induced drag of the generating surface.

Numerous experimental investigations have been conducted to understand the tip vortex structure and its dissipation or persistence. Shekarriz, Fu, Katz, and Huang (1993) studied the evolution of the blade tip vortex by mapping its instantaneous lateral velocity at several consecutive axial locations. They also measured the axial velocity distribution. Cai (2006) carried out experimental investigations on blade tip vortex. They found that the blade sheds multiple vortices. The interaction of the vortices gives rise to the unsteady motion of the blade tip vortex. Devenport, Rife, Liapis, and Follin (1996) performed experiments on the tip vortex generated from a rectangular NACA 0012 half-wing. A very important conclusion of their work is that the vortex is laminar. Chow, Zilliac, and Bradshaw (1997) took measurements of a blade tip vortex. They found that the turbulence in the tip vortex decayed quickly along stream-wise direction. Spalart (1998) gave a review on the wingtip vortex. Anderson and Lawton (2003) found the relationship between the vortex strength and axial velocity in a trailing vortex. However, their results indicated that the magnitude of the axial velocity is sensitive to the two end-cap configurations (flat and rounded). There are also some experiments on controlling wing tip vortex.

Young and Squire (1942) did examining a typical lift curve and the corresponding nature of flow over an airfoil; found that the loss of lift at high angles of attack is closely associated with flow separation on the suction surface of an airfoil. Therefore, it is traditionally believed that maintaining an attached flow there is crucial and critical in lift generation. Nonetheless, experimental studies reported by Cox (1973) on wings with specially designed flaps, known as the Kasper wing, and by Buckholz (1986) on a corrugated airfoil confirm that separated flow involving trapped vortices lead to a modification of the effective wing shape and thereby is beneficial for lift enhancement. Another well-known example is that some vortical flow is formed on the upper surface, inducing large suction peaks and giving rise to “vortex lift” as elucidated in Hummel (1978). Theoretical studies by Saffman and Sheffield (1977) on a flat-plate airfoil, and Rossow (1992) on an airfoil fitted with two fences over the upper surface both indicate that the lift augmented by a stably trapped vortex is significant. Recently, there is a study by Bunyakin, Chernyshenko, and Stepanov (1998) of flow past an airfoil with a vortex trapped in a cavity to enhance the aerodynamic characteristics. Huang and Chow (1982) demonstrated theoretically how an external potential vortex could increase the lift on an airfoil when the Kutta condition was reinforced at its trailing edge in an incompressible, irrotational flow by using conformal mapping. Subsequently, their calculations indicated that a stationary vortex would be uniquely determined on the upper surface of a smooth Joukowsky airfoil when one of the coordinates of the vortex core is specified. The motion of potential vortices has been extensively documented in the literature. Typical examples include Saffman and Sheffield (1977) , Conlisk and Rockwell (1981), Huang and Chow (1982), Panaras (1985), Rossow (1992), De Laat and Coene (1995), Yeung (2001), Crowdy and Marshall (2006) and Zannetti (2006).

The study of literature review shows that is possibility to use trap vortex concept to increase the performance of airfoil.

This experiment analyzes the NACA 0015 airfoil in a low-speed wind tunnel at varying angles of attack. The NACA 0015 is a symmetrical airfoil with a 15% thickness to chord ratio. Symmetric airfoils are used in many applications including aircraft vertical stabilizers, submarine fins, rotary and some fixed wings. Two dimensions and three dimensions blade models are analyzed at 15, 20, and 25 m/sec speeds for obtaining lift coefficient. The experiment also observed the change in increase of lift when the velocities (15, 20 and 25 m/sec) and angle of attack (20, 25, 30, 35 and 40) are varied during each experimental run. This is important in understanding the stall characteristics of this airfoil.

3. Experimental set-up

The blade profile is a NACA 0015 with a chord of 0.05m and a 0.0225m maximum thickness see figure 1. It was made from acrylate material (polymer) by using rapid prototyping machine see figure2. The resulting surface is smooth without artificial roughness. The blade is mounted in the OLLS wind tunnel with a closed square test-section of 0.40 m width. The wind stream is produced by a centrifugal fan with an electric power of 10 Hp (maximum). The maximum velocity in the test-section is 40 m/s. The airfoil has a 30% chord and the model is oriented vertically in the tunnel for this 3D and 2D test as shown in figure 3.

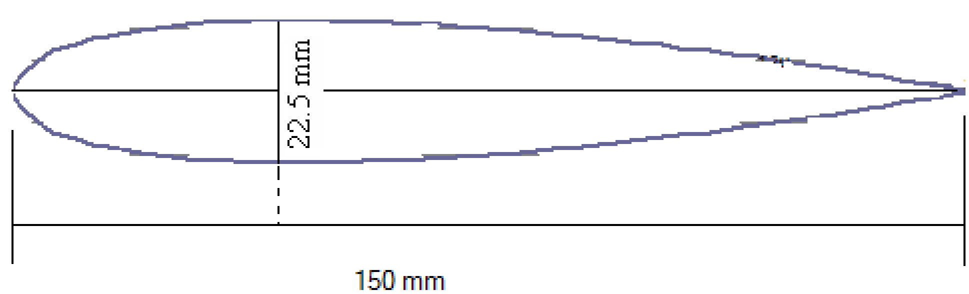


Fig 1: Sketch of an airfoil NACA 0015 (the maximum thickness at 30% of chord)

Fig 2: The real model of NACA0015 airfoil

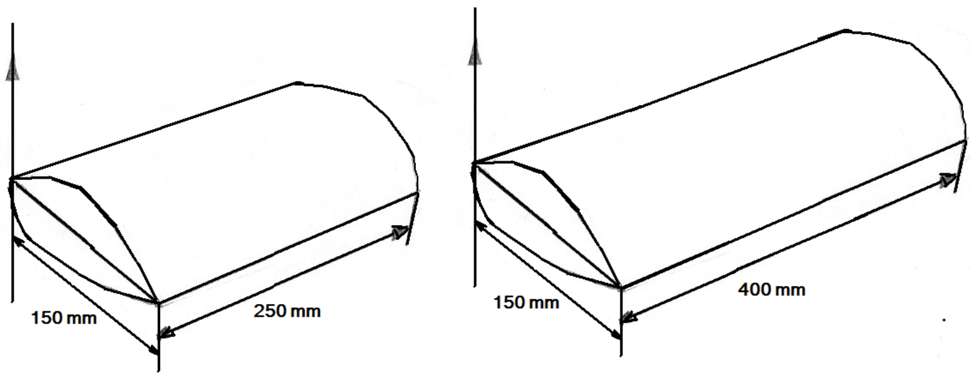


Fig 3: Shows the three-dimensional diagram for two models

4. Apparatus and instrumentation

The experiment was conducted in the subsonic speed wind tunnel. This is an opened-loop atmospheric wind tunnel capable of maximum velocities of 40 m/s see figure 4. The type of NACA 0015 airfoil used in the experiment is made of composite materials named acrylate (polymer material) and it was mounted in the center of the test section. A handle outside of the wind tunnel attached to the airfoil was used to adjust the angle of attack. This was determined using a protractor also mounted on the outside of the test section. The model contained 21 pressure taps located along its bisector. These pressure taps were then connected via rubber tubing to a manometer-tube and by closely monitoring the change in the water level of in the manometer tube the data were obtained. The locations of these pressure tappings are shown below in Figure 5.

Fig 4: Shows the blade inside wind tunnel

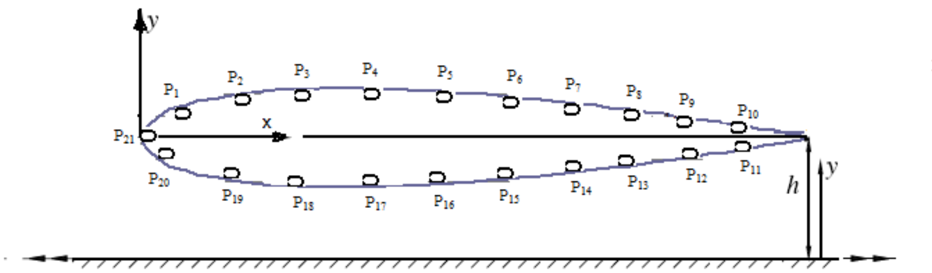


Fig 5: NACA 0015 airfoil cross-section with pressure tapping's

The level water observed in the manometer-tubes allowed various measurements to be taken for each pressure tap individually and progressively incremented one by one throughout the reading.

5. Experimental procedure

The first set of experiment involves setting the airfoil at 15 m/s velocity wind tunnel while the angle of attack is varied from 20, 25, 30, 35 and 40. The next sets of experiment involves setting the same airfoil at wind tunnel velocities of 20 m/sec and 25 m/sec under various angle of attack of 20, 25, 30 35 and 40. The behavior of the streamers on the suction side of the airfoil was closely monitored during the afore-mentioned experiments. This set of experiment was then performed on the airfoil as follows;

- When there is no groove on the airfoil;
- When one groove is at leading edge of the airfoil;

- When one groove is at the center airfoil; and
- When both grooves were on the airfoil.

6. Analysis

The trapezoidal rule is used several times throughout the analysis in order to numerically carry out required integration of the measured data. The following is the trapezium rule Gilat and Subramaniam (2008).

$$I(f) \approx \frac{[f(a) + f(b)]}{2}(b - a) \qquad (1)$$

This is a simple geometric approximation to the area under the curve 'f' by assuming the change between any two points a and b is linear. The following three equations were used in order to determine the measured coefficients of lift from the pressure tap data.

$$C_{F_x} = \frac{1}{c}\int_{y_{x=0}}^{y_{x=c}} \left(C_{p_u} - C_{p_l}\right) dy \qquad (2)$$

$$C_{F_y} = -\frac{1}{c}\int_{0}^{c} \left(C_{p_u} - C_{p_l}\right) dx \qquad (3)$$

$$C_L = -C_{F_x} \sin\alpha + C_{F_y} \cos\alpha \qquad (4)$$

All integration required in these equations was accomplished using the trapezoidal rule described above by using Matlab 7.1 software.
The NACA 0015 airfoil is relatively thin and symmetric. Because of this, thin airfoil theory was applied in order to determine the theoretical values of the lift coefficients. The following equation relates the coefficient of lift to the angle of attack for thin symmetrical airfoils Anderson Jr (2010).

$$C_L = 2\pi\alpha \qquad (5)$$

7. Results and discussions

While keeping the tunnel velocity constant and varying the angle of attack, the characteristics of the flow were obtained. As angle of attack is increased, the flow will eventually separate from the upper surface of the airfoil resulting in a 'stall'. It was noted that the angle of attack must be decreased below the separation angle of attack in order for the flow to reattach. This phenomenon is known as hysteresis. The same can be seen by setting the angle of attack and decreasing the tunnel velocity until separation occurs. The velocity must be increased higher than the velocity at which the flow separated in order to reattach and also it was noted that the increasing angle of attack more than 20 degree as in this work, the curve keeps going up and then the stall started after 45-degree angle of attack was reached.

There were two models in these, the 2D and 3D models were of 400 mm and 250 mm in length respectively. The following figures are plots of the coefficient lift (C_L) versus the angle of attack.

7.1 Result of 2D tests

Figure 6 shows relation between lift coefficient and angle of attack at velocity of 15 m/sec it was noted that the values of C_L is smaller than the values of published data in the case of no groove. There was 3.67% increase in the lift for one groove at the center of airfoil, 4.8% increase for one groove at leading edge and the highest increase of 6.41% occurred for two grooves.

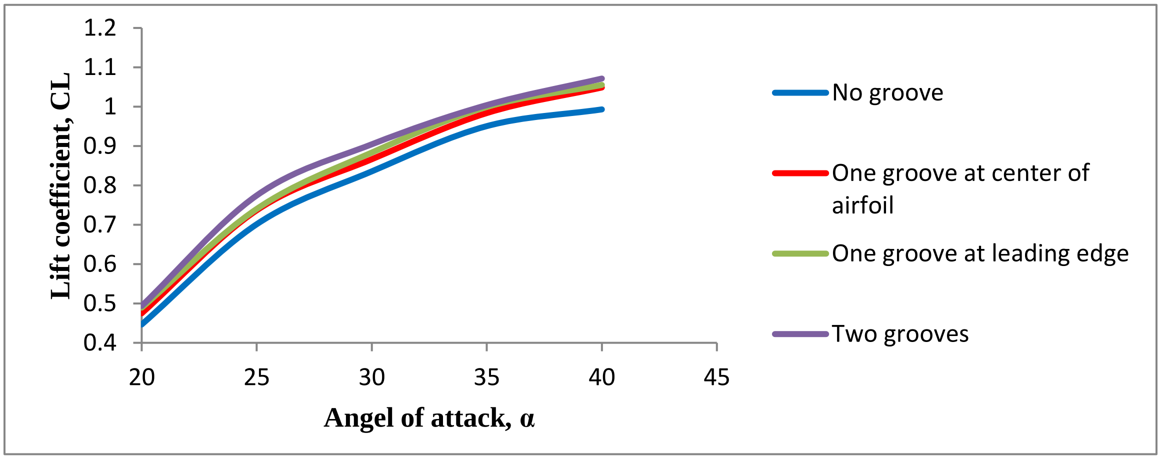


Fig 6: Shows relation between lift coefficient and angle of attack at 15 m/sec.

Figure 7 shows relation between lift coefficient and angle of attack at velocity of 20 m/sec it was noted that the values of C_L is smaller than the values of published data in the case of no groove. There was 3.97% increase in the lift for one groove at the center of airfoil, 6.02% increase for one groove at leading edge and the highest increase of 7.97% occurred for two grooves.

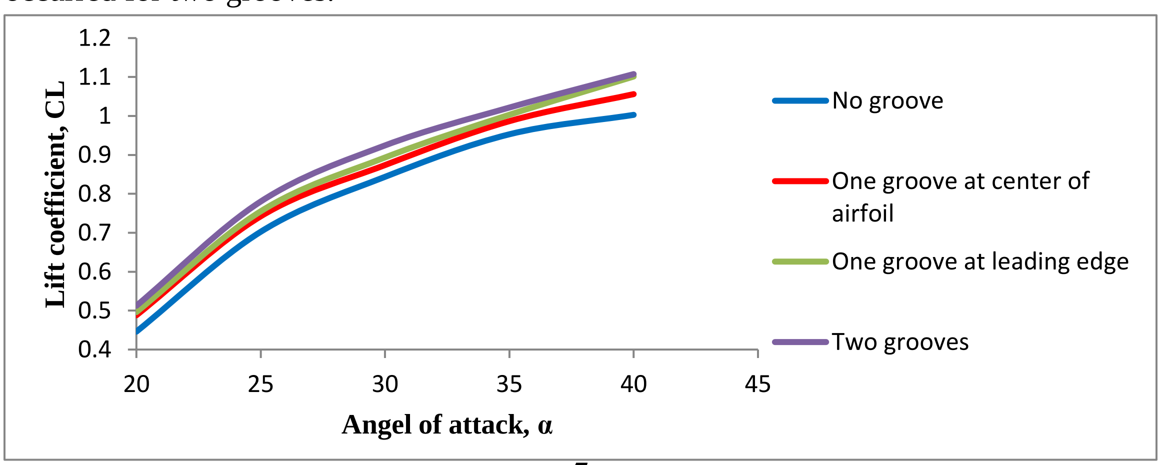


Fig 7: Shows relation between lift coefficient and angle of attack at 20 m/sec

Figure 8 shows relation between lift coefficient and angle of attack at velocity of 25 m/sec it was noted that the values of C_L is smaller than the values of published data in the case of no groove. There was 3.6% increase in the lift for one groove at the center of airfoil, 6.51% increase for one groove at leading edge and the highest increase of 10.45% occurred for two grooves.

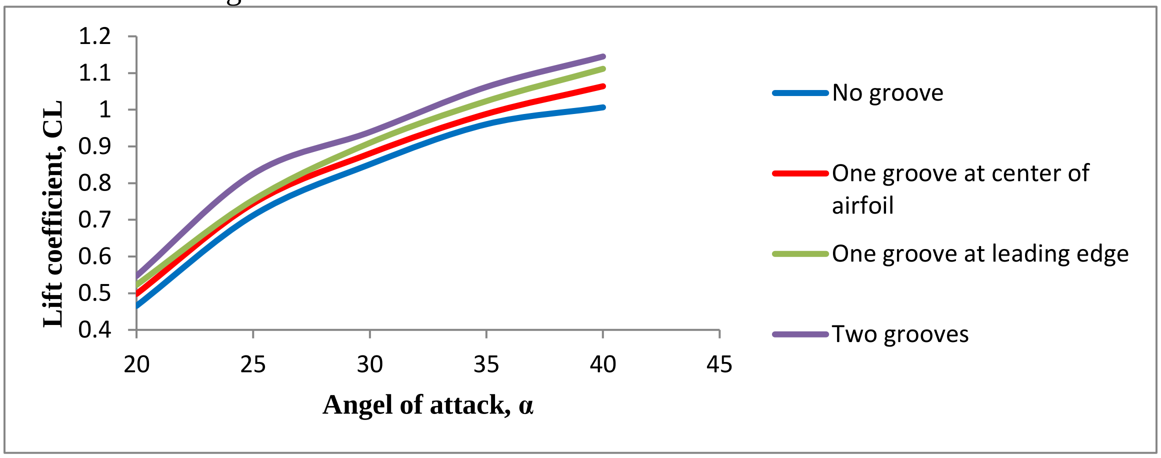


Fig 8: Shows relation between lift coefficient and angle of attack at 25 m/sec

From Figures 6, 7 and 8 it can be deduced that an increase in the lift coefficient for one groove at leading edge showed better results than results from one groove at center of airfoil. Also, the two grooves.

The results of these experiments were then compared to the published data of lift coefficient done by Sheldahl and Klimas (1981). Below are some of the outcomes.

i). From figure 9 it is seen that both the graphs are in good agreement with a small deviation of 2.3% at 15 m/sec. The graphs are shown in figure 9.

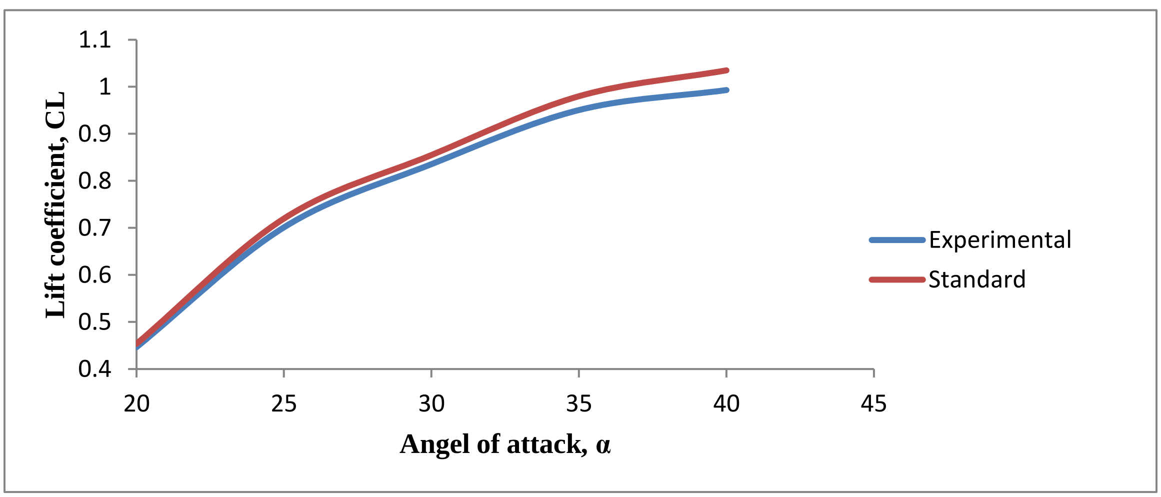


Fig 9: Shows relation between lift coefficient and angle of attack at 15 m/sec for published values and experimental results

ii). From figure 10 it is seen that both the graphs are in good agreement with a small deviation of 2.3% at 20 m/sec. The graphs are shown in figure 10.

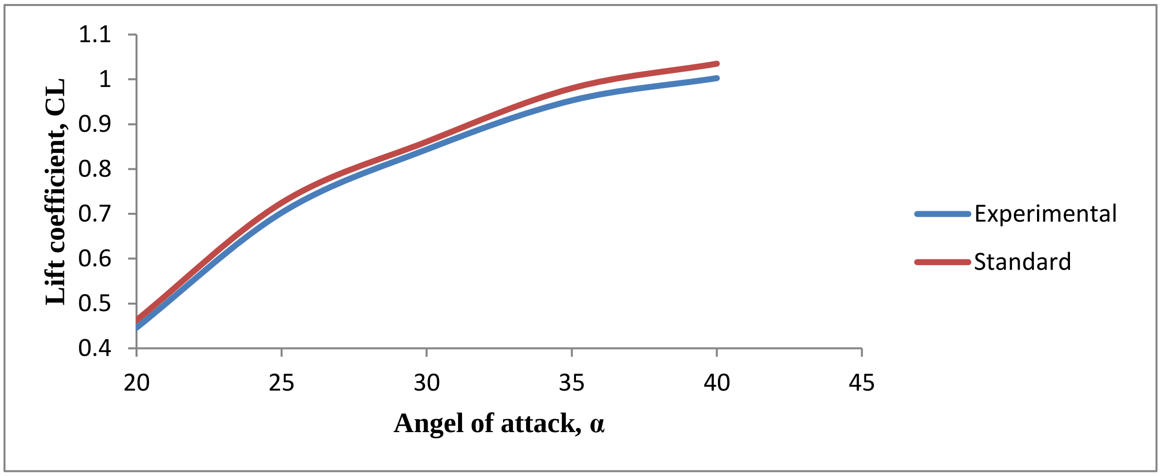


Fig 10: Shows relation between lift coefficient and angle of attack at 20 m/sec for published values and experimental results

iii). From figure 11 it is seen that both the graphs are in good agreement with a small deviation of 2.11% at 25 m/sec. The graphs are shown in figure 11.

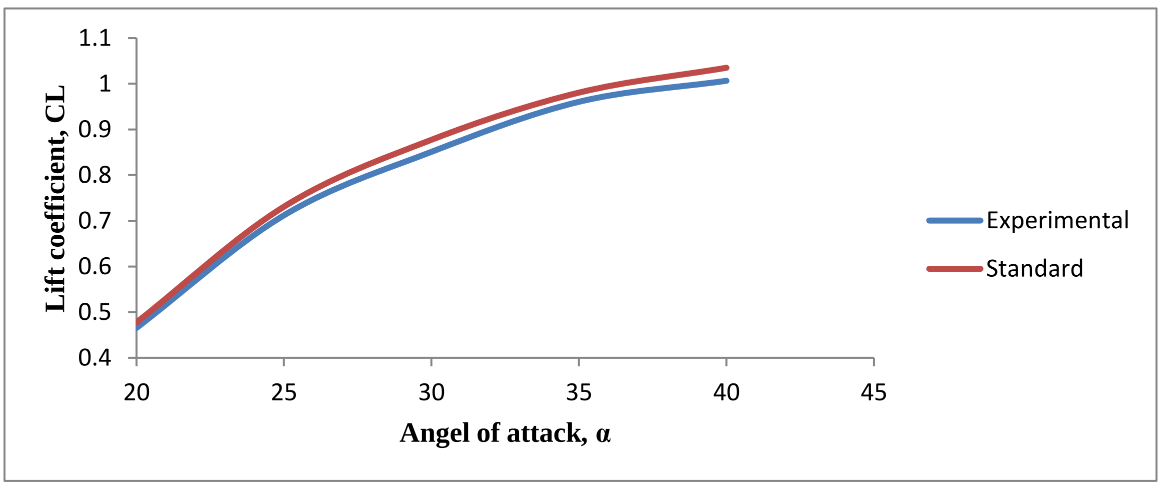


Fig 11: Shows relation between lift coefficient and angle of attack at 25 m/sec for published values and experimental results

From the above figures (9, 10 and 11) it has been observed that slight deviation has occurred between the curves of the experimental results and published data. The deviation is just 2.3% for the experimental run involves 15 m/sec and 20 m/sec and

2.11% experimental for 25 m/sec. These are quite negligible. Thus, it can be said that these results acceptable accurate and were validated.

7.2 Result of 3D tests

1) The results of lift coefficient for distribution pressure at end of airfoil for 25 cm length model.

Figure 12 shows relation between lift coefficient and angle of attack at 15 m/sec for 3D test at velocity of 15 m/sec it was noted that the values of C_L is higher than the values of published data in the case of no groove. There was 1.18% increase in the lift for one groove at the center of airfoil, 3.38% increase for one groove at leading edge and the highest increase of 7.98% occurred for two grooves.

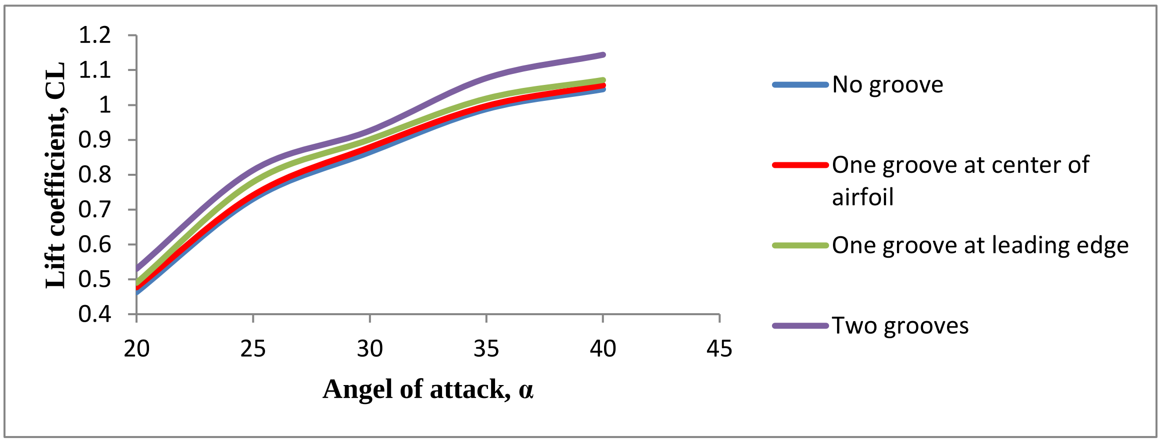


Fig 12: Shows relation between lift coefficient and angle of attack at 15 m/sec for 3D test.

Figure 13 shows relation between lift coefficient and angle of attack at 20 m/sec for 3D test at velocity of 20 m/sec it was noted that the values of C_L is higher than the values of published data in the case of no groove. This was due to error in taking reading during the experiments or error due to the facility. There was 1.31% increase in the lift for one groove at the center of airfoil, 4.31% increase for one groove at leading edge and the highest increase of 9.41% occurred for two grooves.

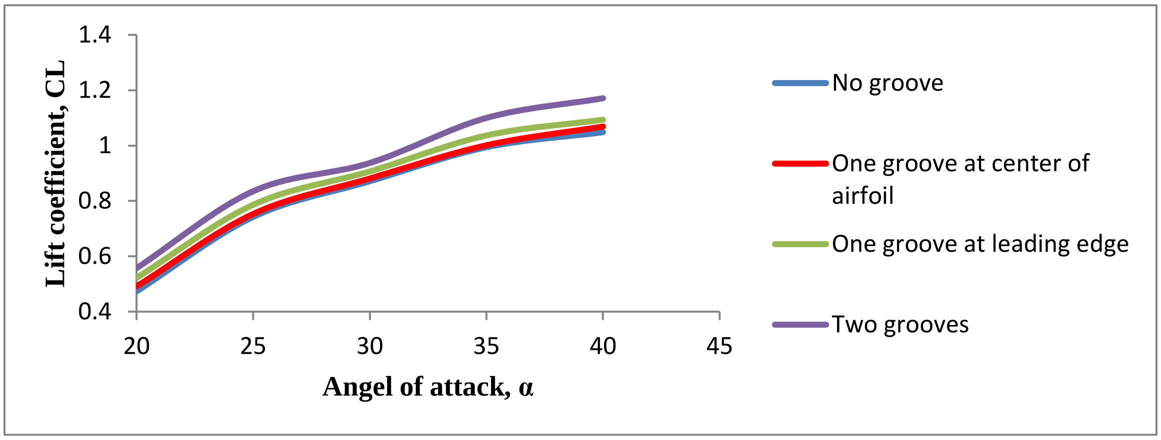
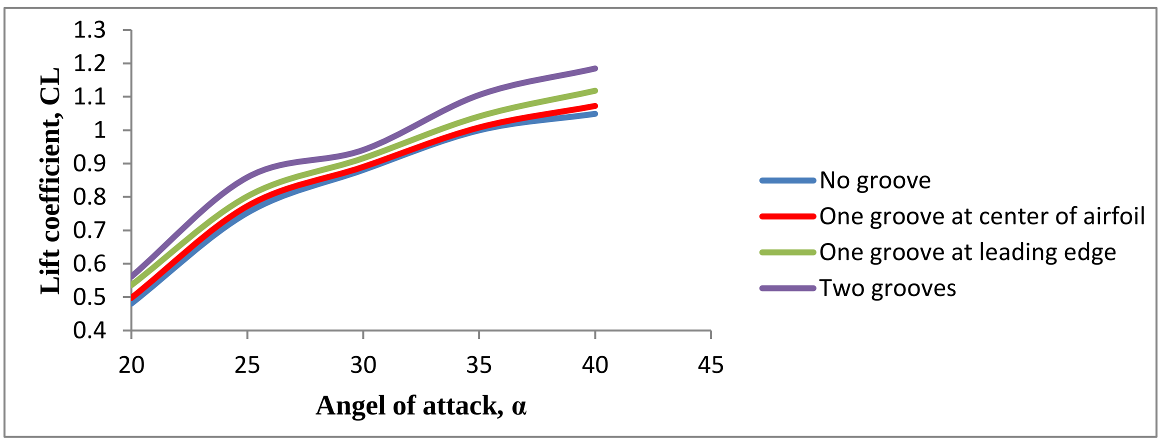


Fig 13: Shows relation between lift coefficient and angle of attack at 20 m/sec for 3D test.

Figure 14 shows relation between lift coefficient and angle of attack at 25 m/sec for 3D test at velocity of 25 m/sec it was noted that the values of C_L is higher than the values of published data in the case of no groove. This was due to error in taking reading during the



experiments or error due to the facility. There was 1.56% increase in the lift for one groove at the center of airfoil, 4.99% increase for one groove at leading edge and the highest increase of 9.76% occurred for two grooves.

Figure 14 Shows relation between lift coefficient and angle of attack at 25 m/sec for 3D test

From Figures 12, 13 and 14 it can be deduced that an increase in the lift coefficient for one groove at leading edge showed better results than results from one groove at center of airfoil and also it was noted that curve of no groove match closely to curve of one groove at center. Also, the two grooves.

The results of these experiments were then compared to the published data of lift coefficient done by Sheldahl and Klimas (1981). Below are some of the outcomes.

i). From figure 15 it is seen that both the graphs are in good agreement with a small deviation of 0.94% at 15 m/sec. The graphs are shown in figure 15.

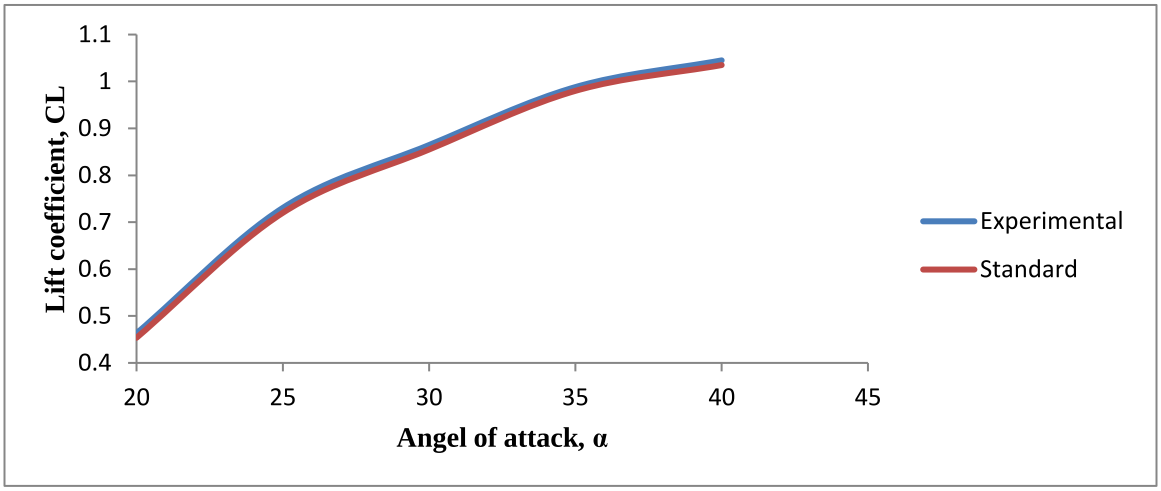


Fig 15: Shows relation between lift coefficient and angle of attack at 15 m/sec for published values and experimental results for 3D test.

ii). From figure 16 it is seen that both the graphs are in good agreement with a small deviation of 0.95% at 20 m/sec. The graphs are shown in figure 16.

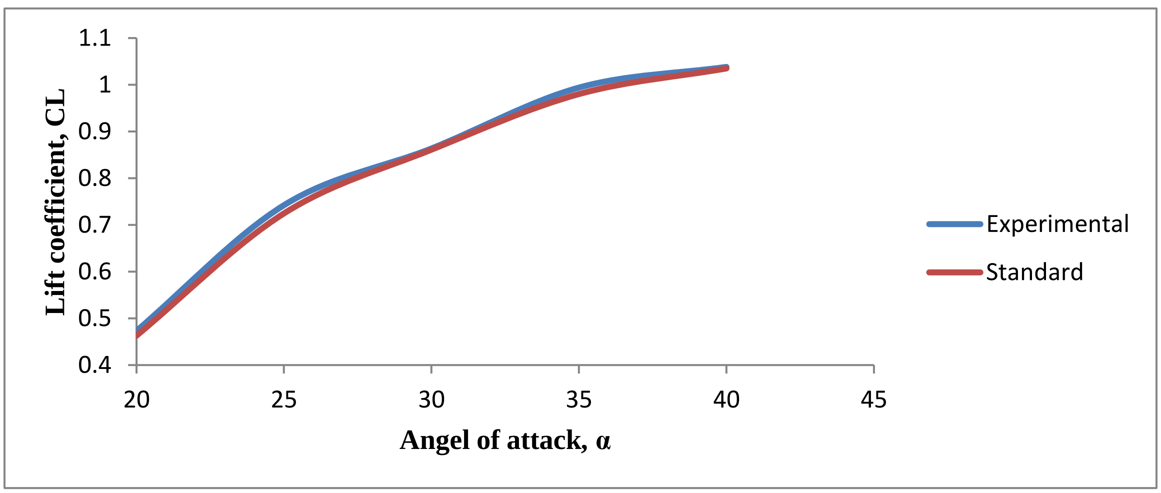


Fig 16: Shows relation between lift coefficient and angle of attack at 20 m/sec for published values and experimental results for 3D test

iii). From figure 17 it is seen that both the graphs are in good agreement with a small deviation of 1.2% at 25 m/sec. The graphs are shown in figure 17.

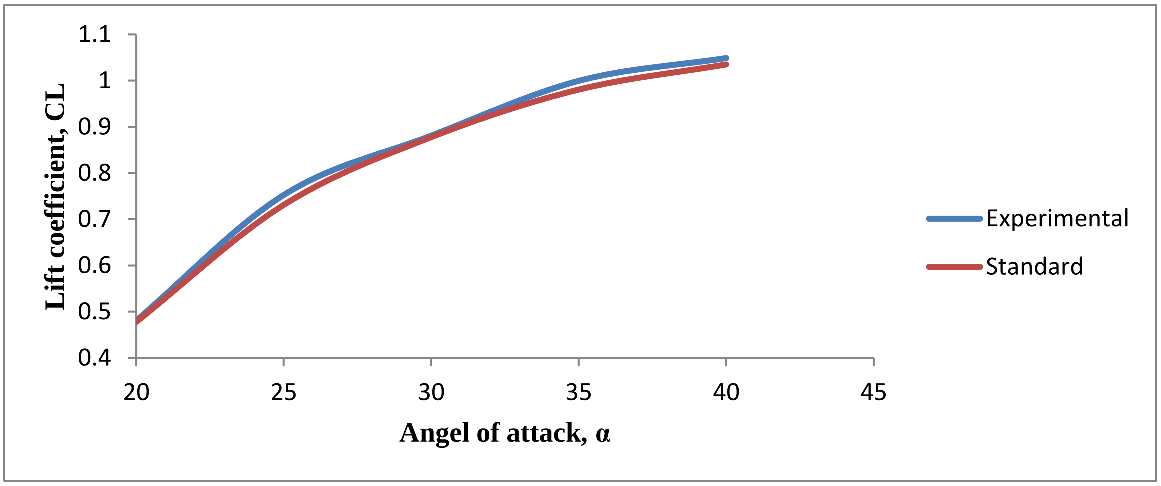


Fig 17: Shows relation between lift coefficient and angle of attack at 25 m/sec for published values and experimental results for 3D test

From the above figures (15, 16 and 17) it has been observed that slight deviation has occurred between the curves of the experimental results and published data. The deviation is just 0.94% for the experimental run involves 15 m/sec and for 20 m/sec is 0.95% and 1.2% experimental for 25 m/sec. These are quite negligible. Thus, it can be said that these results acceptable accurate and were validated.

2) The results of lift coefficient for distribution pressure at center of airfoil for 25 cm length model.

Figure 18 shows relation between lift coefficient and angle of attack at 15 m/sec for 3D test, (center of airfoil) at velocity of 15 m/sec it was noted that the values of C_L is smaller than the values of published data in the case of no groove. This was due to error in taking reading during the experiments or error due to the facility. There was 3.78% increase in the lift for one groove at the center of airfoil, 6.1% increase for one groove at leading edge and the highest increase of 8.7% occurred for two grooves.

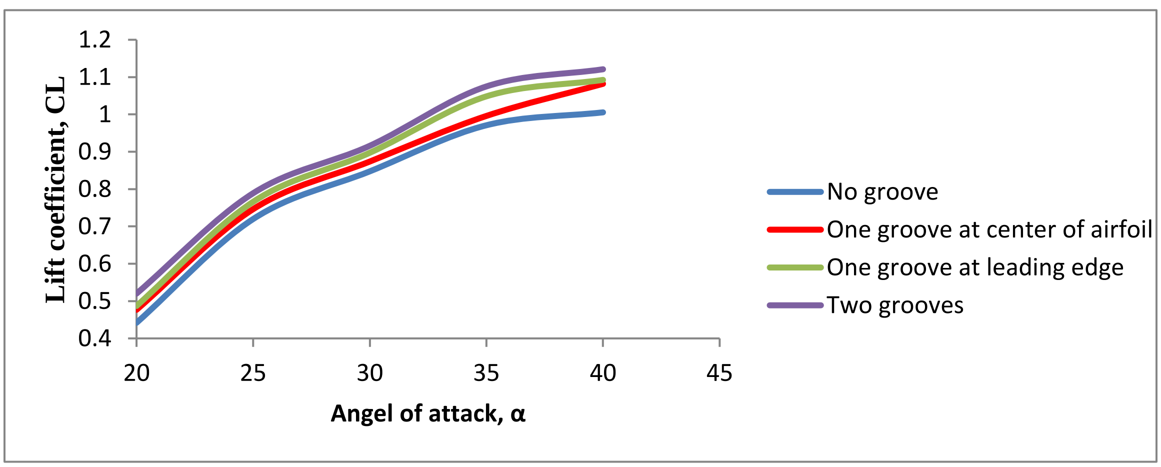


Fig 18: Shows relation between lift coefficient and angle of attack at 15 m/sec for 3D

test, (center of airfoil)

Figure 19 shows relation between lift coefficient and angle of attack at 15 m/sec for 3D test, (center of airfoil) at velocity of 20 m/sec it was noted that the values of C_L is smaller than the values of published data in the case of no groove. This was due to error in taking reading during the experiments or error due to the facility. There was 3.784% increase in the lift for one groove at the center of airfoil, 6.48% increase for one groove at leading edge and the highest increase of 6.26% occurred for two grooves.

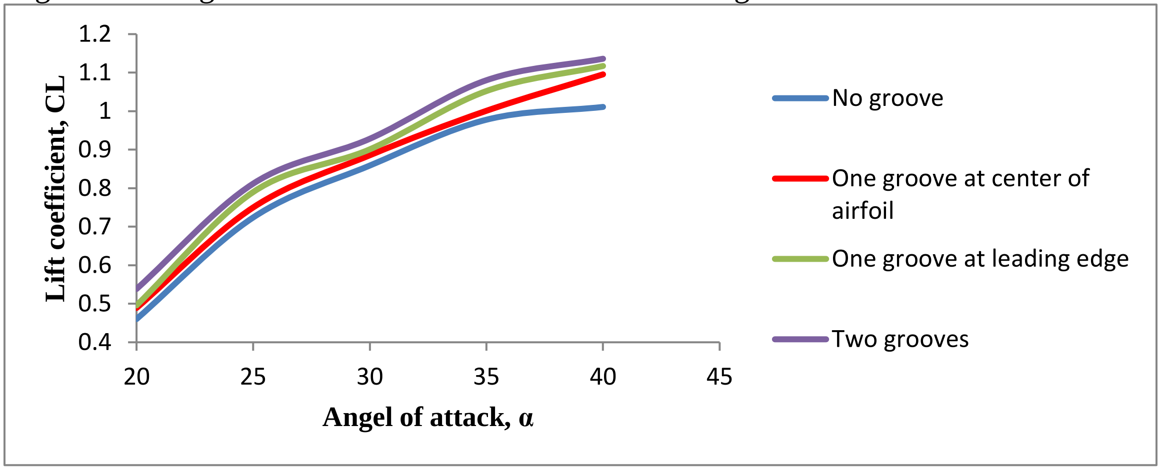


Fig 19: Shows relation between lift coefficient and angle of attack at 20 m/sec for 3D test, (center of airfoil)

Figure 20 shows relation between lift coefficient and angle of attack at 15 m/sec for 3D test, (center of airfoil) at velocity of 25 m/sec it was noted that the values of C_L is smaller than the values of published data in the case of no groove. This was due to error in taking reading during the experiments or error due to the facility. There was 3.85% increase in the lift for one groove at the center of airfoil, 7.36% increase for one groove at leading edge and the highest increase of 10.02% occurred for two grooves.

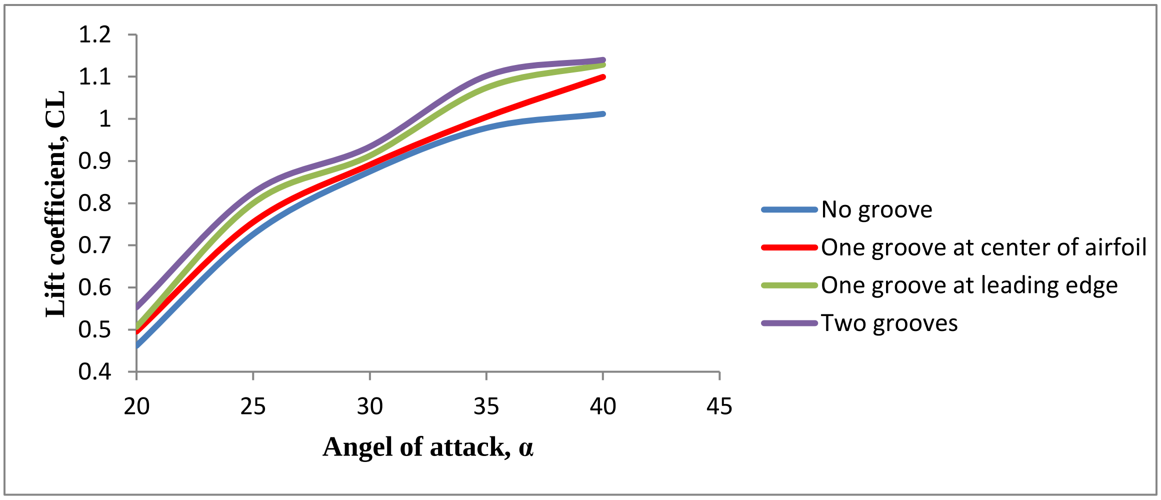


Fig 20: Shows relation between lift coefficient and angle of attack at 25 m/sec for 3D

test, (center of airfoil)

From Figures 18, 19 and 20 it can be deduced that an increase in the lift coefficient for one groove at leading edge showed better results than results from one groove at center of airfoil. Also, the two grooves.

The results of these experiments were then compared to the published data of lift coefficient done by Sheldahl and Klimas (1981). Below are some of the outcomes.

i). From figure 21 it is seen that both the graphs are in good agreement with a small deviation of 1.15% at 15 m/sec. The graphs are shown in figure 21.

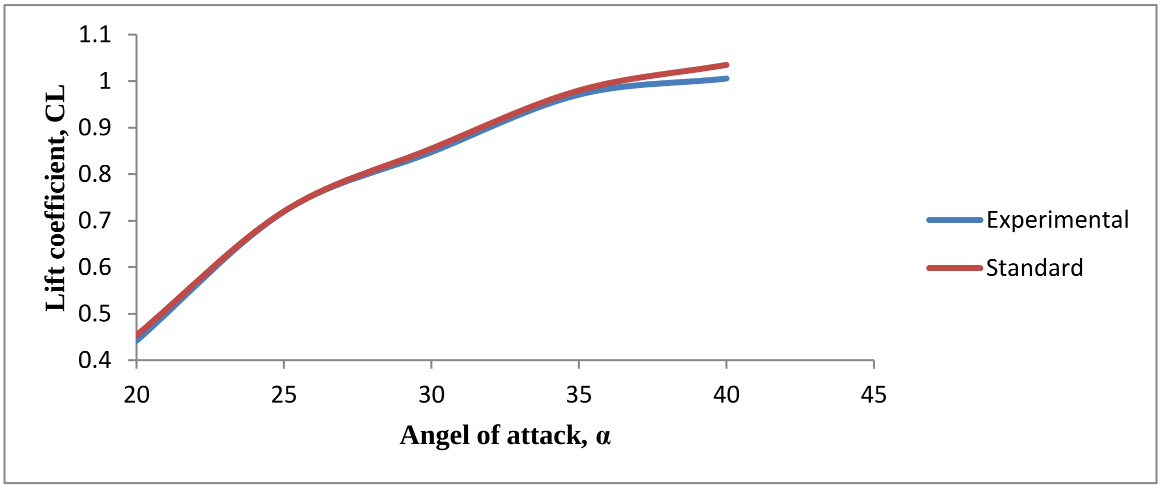


Fig 21: Shows relation between lift coefficient and angle of attack at 15 m/sec for published values and experimental results for 3D test, (at center of airfoil)

ii). From figure 22 it is seen that both the graphs are in good agreement with a small deviation of 0.64% at 20 m/sec. The graphs are shown in figure 22.

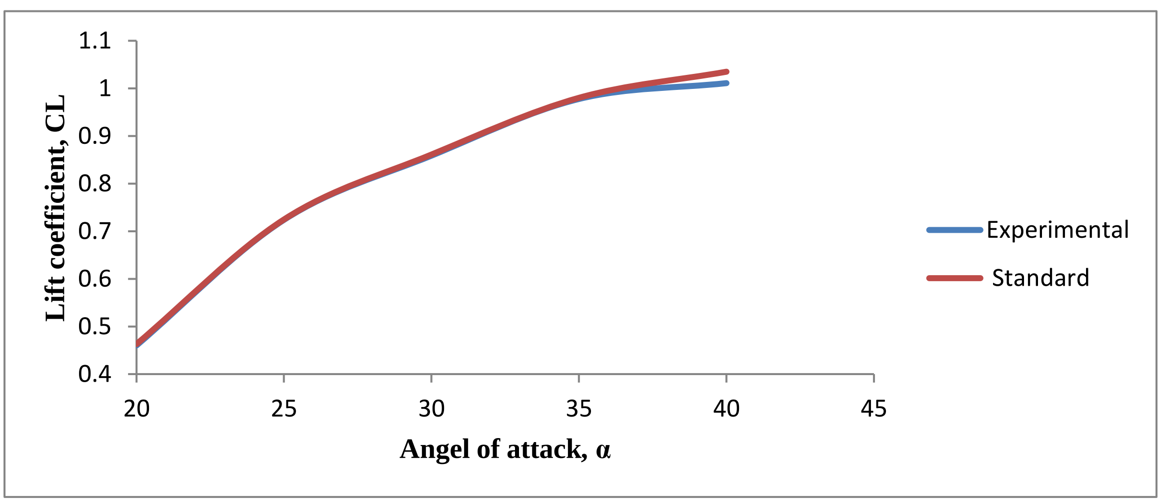


Fig 22: Shows relation between lift coefficient and angle of attack at 20 m/sec for published values and experimental results for 3D test, (at center of airfoil)

iii). From figure 23 it is seen that both the graphs are in good agreement with a small deviation of 0.98% at 25 m/sec. The graphs are shown in figure 23.

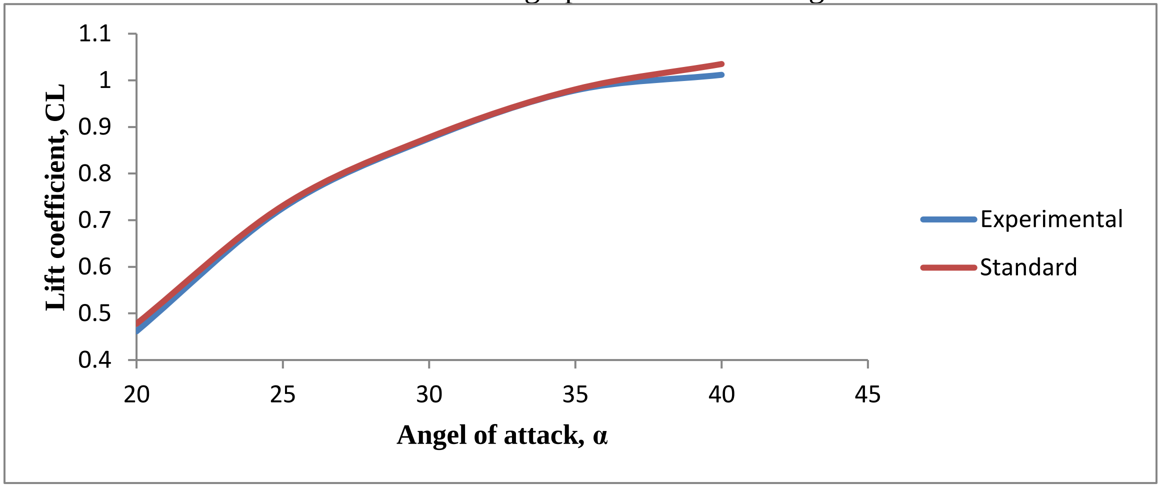


Fig 23: Shows relation between lift coefficient and angle of attack at 25 m/sec for published values and experimental results for 3D test, (at center of airfoil)

From the above figures (21, 22 and 23) it has been observed that slight deviation has occurred between the curves of the experimental results and published data. The deviation is just 1.15% for the experimental run that involves 15 m/sec and for 20 m/sec is 0.64% and 0.98% experimental for 25 m/sec. These are quite negligible. Thus, it can be said that these results acceptable accurate and were validated.

8. Conclusion

The NACA 0015 airfoil was analyzed for the lift coefficient as planned. The measured values determined from lab data were in good agreement with the published values for the coefficient of lift. The main objective of this study was to obtain increase in lift coefficient, hence by using different velocities, various angles of attack and trap vortices. Lift coefficient enhancement was obtained. It was also noted that there was an increase in the lift coefficient for one groove at the center, a more increase in the lift coefficient for one groove at leading edge and the highest increase of life coefficient occurred for two grooves, all of these compared to no groove. A comparison was made between experimental results from this study and published experimental data, which involve the use of NACA 0015 and the values of lift coefficient, were quite accurate when compared to published data. In the experiment for NACA 0015 it was observed that the angle of attack and velocity increase lead to the lift coefficient being increased. Reynolds's numbers varied between 131761 and 220332 for this experiment.

9. References

Anderson, E. A., & Lawton, T. A. (2003). Correlation between vortex strength and axial velocity in a trailing vortex. *Journal of aircraft, 40*(4), 699-704.

Anderson Jr, J. D. (2010). *Fundamentals of aerodynamics*: Tata McGraw-Hill Education.

Buckholz, R. (1986). The functional role of wing corrugations in living systems.

Bunyakin, A., Chernyshenko, S., & Stepanov, G. Y. (1998). High-Reynolds-number Batchelor-model asymptotics of a flow past an aerofoil with a vortex trapped in a cavity. *Journal of Fluid Mechanics, 358*, 283-297.

Cai, J. (2006). *LES for wing tip vortex around an airfoil*: The University of Texas at Arlington.

Chow, J. S., Zilliac, G. G., & Bradshaw, P. (1997). Mean and turbulence measurements in the near field of a wingtip vortex. *AIAA journal, 35*(10), 1561-1567.

Conlisk, A., & Rockwell, D. (1981). Modeling of vortex-corner interaction using point vortices. *The Physics of Fluids, 24*(12), 2133-2142.

Cox, J. (1973). The revolutionary Kasper wing. *Soaring, 37*, 20-23.

Crowdy, D., & Marshall, J. (2006). The motion of a point vortex through gaps in walls. *Journal of Fluid Mechanics, 551*, 31-48.

De Laat, T., & Coene, R. (1995). Two-dimensional vortex motion in the cross-flow of a wing-body configuration. *Journal of Fluid Mechanics, 305*, 93-109.

Devenport, W. J., Rife, M. C., Liapis, S. I., & Follin, G. J. (1996). The structure and development of a wing-tip vortex. *Journal of Fluid Mechanics, 312*, 67-106.

Gilat, A., & Subramaniam, V. (2008). *Numerical methods for engineers and scientistsan introduction with applications using MATLAB*: Wiley.

Huang, M.-K., & Chow, C.-Y. (1982). Trapping of a free vortex by Joukowski airfoils. *AIAA journal, 20*(3), 292-298.

Hummel, D. (1978). *On the Vortex Formation over a Slender Wing at Large Angles of Attack, High Angle of Attack Aerodynamics.* Paper presented at the AGARD.

Kasper, W. A. (1975). *Some ideas of vortex lift* (0148-7191). Retrieved from

Panaras, A. G. (1985). Pressure pulses generated by the interaction of a discrete vortex with an edge. *Journal of Fluid Mechanics, 154*, 445-461.

Ringleb, F. O. (1961). Separation control by trapped vortices. *Boundary layer and flow control, 1*, 265.

Rossow, V. J. (1992). Two-fence concept for efficient trapping of vortices on airfoils. *Journal of aircraft, 29*(5), 847-855.

Saffman, P., & Sheffield, J. (1977). Flow over a wing with an attached free vortex. *Studies in Applied Mathematics, 57*(2), 107-117.

Shekarriz, A., Fu, T., Katz, J., & Huang, T. (1993). Near-field behavior of a tip vortex. *AIAA journal, 31*(1), 112-118.

Sheldahl, R., & Klimas, P. (1981). Aerodynamic characteristics of seven airfoil sections through 180 degrees of attack for use in aerodynamic analysis of vertical axis wind turbines, SAND80-2114. *Sandia National Laboratories, Albuquerque, NM*.

Spalart, P. R. (1998). Airplane trailing vortices. *Annual Review of Fluid Mechanics, 30*(1), 107-138.

Yeung, W. (2001). Theoretical model for airfoils to suppress leading-edge separation. *AIAA journal, 39*(6), 1006-1010.

Young, A., & Squire, H. (1942). A Review of Some Stalling Research With an Appendix on Wing Sections and their Stalling Characteristics.

Zannetti, L. (2006). Vortex equilibrium in flows past bluff bodies. *Journal of Fluid Mechanics, 562*, 151-171.