Vol. 7, No. 2 | July – December 2024

An experimental and numerical investigation on aerodynamic characteristics for different airfoil sections for external flow

Irsa Talib*[1], Ahmad Zafar[1], Muhammad Furqan[1], Zeshan Ahmad[1], Jawad Hussain[2], Nasif Raza Jaffri[3]

Abstract:

The safety and reliability of aircraft depends on both electrical and mechanical design considerations. This research presents the development of a subsonic wind tunnel designed for streamlined airflow, featuring a squared cross-sectional area along its length. The primary focus is on measuring drag and lift on external flow across two different airfoil models. Utilizing a variable-speed centrifugal blower motor in the absence of converging and diverging sections ensures streamlined airflow in the test section. Two airfoil models, NACA-0012 and NACA-2414, fabricated from galvanized iron thin gauge sheet metal, undergo analysis through wind tunnel experiments and numerical simulation. Within the wind tunnel, strain gauge load cells are incorporated to accurately measure drag and lift across the airfoils. Comparative assessments of drag and lift coefficients are conducted at four varying angles of attack (-6.3 degrees to 12.6 degrees) for each airfoil. Results from both wind tunnel experiments and numerical simulations demonstrate precision, closely aligning with literature.

Keywords: *Airfoil, Airflow, Drag, External flow, Lift, Wind tunnel*

1. Introduction

Aerospace and avionics make use of various fields of electrical engineering including telemetry, power bus design, electromechanical actuators, feedback control systems, digital computer specification and programing. Furthermore, the utilization of wind tunnels has been a cornerstone in the exploration of aerodynamics, offering a controlled environment for the meticulous examination of the aerodynamic features inherent in a myriad of everyday objects, ranging from automobiles and aircraft to architectural structures and maritime vessels [1, 2]. This indispensable experimental apparatus plays a pivotal role not only in understanding the intricacies of airflow but also in refining designs to enhance lift and mitigate drag.

In the context of aerodynamic investigations, a crucial component of wind tunnel experimentation involves subjecting airfoils to rigorous testing [3]. Whether full-scale or scaled-down, airfoils are meticulously mounted within the wind tunnel during dedicated airfoil tests. Within the confines of this controlled environment, the wind tunnel simulates various flying scenarios by manipulating the flow of air over the airfoil at different velocities and angles of attack [4]. The orchestrated interplay between high-speed fans and the airfoil generates controlled and uniform airflow, thereby producing discernible lift and drag forces. The results of these tests yields important data such as lift, drag, moment, and pressure distribution across the airfoil surface. This dataset is then used by engineers to modify the airfoil's structure by changing its shape, attack angle, and other relevant features. These simulations provide valuable insights on the impact of modifications in these parameters on the overall performance of the airfoil [5].

The aerodynamic losses are further discussed by some researchers [6, 7]. They took the wind tunnel research and explained the aerodynamics for equipment used transportation, aviation, and sports industries [6, 7]. These implications of wind tunnel

[1]Department of Mechanical Engineering, University of Management and Technology, Lahore, Punjab, Pakistan

[1] Office of Research Innovation and Commercialization, University of Management and Technology, Lahore, Punjab, Pakistan

[2] Department of Biomedical Engineering, Riphah International University, Lahore, Punjab, Pakistan

[3]Department of Electrical Engineering, NFC Institute of Engineering and Fertilizer Research, Faisalabad Punjab, Pakistan

*Corresponding author's e-mail: irsatalib@gmail.com

urged the scientists to develop subsonic wind tunnels, specifically designed to investigate the aerodynamic behaviors of scaled-down airfoil designs. These updated designs integrates many sophisticated sensors and instruments to get the accurate recordings and readings of factors such as lift and drag coefficients during the experimental phase to test new designs [8].

The design of a wind tunnel with the ability of generating turbulent airflow in a subsonic range is the primary consideration for this research. Turbulent airflow would play a crucial role as it would reduce the boundary layer thickness and also minimize the effects of wake region on airfoil prototypes. This incorporation forms part of the quest for full test scenarios in the wind tunnel so that results are accurate and properly conserved. This research investigates different airfoil designs alongside lift and drag coefficients at different angles of attack, with all the testing at a Reynolds number of 100,000.

The experimental results are compared with simulated ones using comparative analysis. These two kinds of empirical data with predictions serves as a litmus test, that helps verifying the methodology used in wind tunnel design [9]. Hence, combined empirical and numerical results of the research purports to further exploration not just at improving the design of airfoils, but also at improving that very understanding of aerodynamics which has applications in other areas.

This research attempts to give a holistic picture about wind tunnel design, encompassing both the historical importance of wind tunnels and current needs for increasing the prowess of subsonic wind tunnels. This would be beneficial, as it would contribute, to the fundamental understanding of aerodynamics, providing much more applicable knowledge in real-life contexts that would apply equally in different industrial sectors.

This article is divided into different sections. In the next sections, we reveal the methodology and results from numerical simulations and wind tunnel experiments and then indulge into thorough discussion on implications and trends that emerge from such a broad exploration in terms of future pathways. This article aims at investigating the aerodynamic behavior of NACA-0012 and NACA-2414 airfoil models using a subsonic wind tunnel. It measures drag and lift under angles of attack varying from -6.3 to 12.6 degrees and co-validates findings through comparative analysis with numerical simulations. Through this work, engineers, researchers, and aerodynamics and wind tunnel experiment fanatics may take the guidance in the complex realm of wind tunnel design and aerodynamics.

2. Methodology

A 3D model of a subsonic wind tunnel was developed in SOLIDWORKS (version 2023) and simulated for results using Ansys Fluent 2020 R1 workbench. The dimensions of 3D model were in match with the blower specifications used in the prototype. The prototype of a subsonic wind tunnel was square-shaped (uniform area of --m^2), open-type, with a section length of 2.13 m. A stand of length 2.74 m and height 0.61 m was used to support the subsonic wind tunnel prototype. The subsonic wind tunnel prototype was made of rust-proof and aesthetically appealing galvanized iron sheet (28-gauge, 1.5 mm thickness). The test section (2 m long) was made with a 5 mm thick acrylic sheet for transparency and durability.

Both NACA-0012 and NACA-2414 airfoils were fabricated from galvanized iron sheets (35-gauge, 1mm thickness). The adhesives were used to join the airfoil parts and which were further grind prior spray painted to smooth the edges and corners. The dimensions for both the airfoils used in this study were taken from Airfoil Tools database. The NACA-0012 was fabricated from a 150mm chord length and symmetry in shape. While, NACA-2414 had an asymmetrical shape to provide high lift for a slight increase in drag. A customized airfoil mounting mechanism was developed to support the airfoil inside the subsonic wind tunnel prototype and vary the angle of attack at four different values including -6.3, 0, 6.3 and 12.6. The airfoil and mounting mechanism were visible through the acrylic test section.

A variable-speed centrifugal blower motor (with maximum air speeds up to 8.8m/s) but its speed was limited to 5.2m/s for our experimental and numerical simulation to compensate for fully developed flow across the test section for better results in the absence of converging and diverging sections. It provided streamlined airflow to the test section reducing swirl and turbulence intensity while minimizing cost in comparison to vacuum exhaust wind tunnel designs [10].

The two-strain gauge load-cells were attached to airfoil mounting mechanism with vary angle of attack [11]. The pins joints were greased prior to insertion, Arduino Uno Rev.3 was calibrated with amplifier HX711 and 2kg load-cell along with LCD display screens (back-light to provide bright visible readings) to show measured load in terms of drag and lift during experimentation. Fig. 1. shows 3D drawing of the complete assembly of subsonic wind tunnel developed through SOLIDWORKS 2022. While Fig. 2. shows the assembly of complete fabrication of prototype including table stand that supports the entire assembly of the prototype.

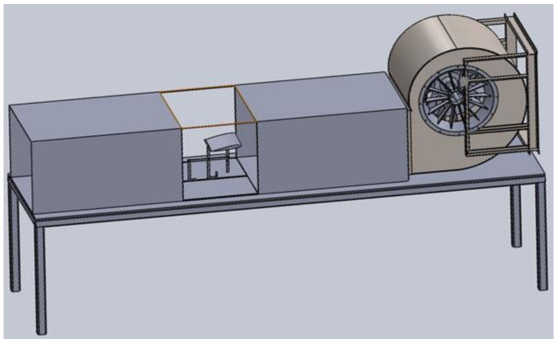

Fig. 1. Wind tunnel assembly

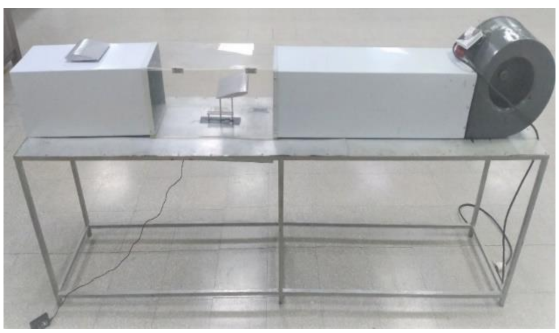

Fig. 2. Wind Tunnel assembly

The drag co-efficient (C_D) and lift co-efficient (C_L) were calculated using equation (1) and (2), respectively, against four different values of α, for both NACA-0012 and NACA-2414 airfoils in simulation through Ansys Fluent 2020 R1 workbench. The C_D and C_L were measured for experimental set up as well [12].

$$\boldsymbol{C_D} = \frac{F_D}{\frac{1}{2}\rho V^2 A} \quad (1)$$

$$\boldsymbol{C_L} = \frac{F_L}{\frac{1}{2}\rho V^2 A} \quad (2)$$

3. Results

The profiles for both airfoils including NACA-0012 and NACA-2414 were drawn as shown in Fig. 3. and Fig. 4. respectively[13]. The numerical C_D (**C_D** (NUM)), experimental C_D (**C_D (EXP)**), numerical C_L (**C_L (NUM)**) and experimental C_L (**C_L (EXP)**) at four different values of α, for NACA-0012, are given in TABLE I. While the numerical C_D (**C_D (NUM)),** experimental C_D (**C_D (EXP)**), numerical C_L (**C_L (NUM)**) and experimental C_L(**C_L (EXP)**) at four different values of α, for NACA-2414, are given in TABLE II.

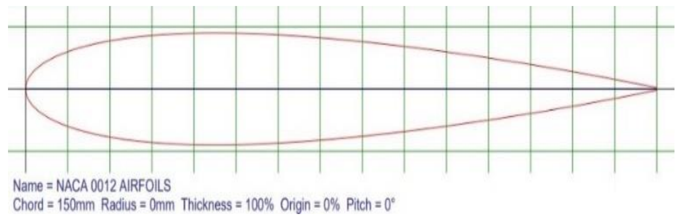

Fig. 3. Airfoil NACA-0012 plot profile [14]

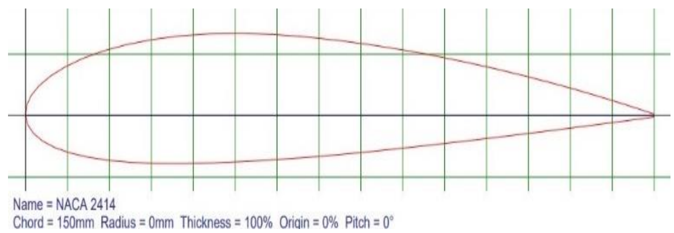

Fig. 4. Airfoil NACA-2414 plot profile [14]

TABLE I. NACA-0012 Ansys Results

NACA-0012 Airfoil Results					
Sr. No	**Angle Of attack (α) in degrees**	**Lift Coefficient, C_L (NUM)**	**Lift Coefficient, C_L (EXP)**	**Drag Coefficient, C_D (NUM)**	**Drag Coefficient, C_D (EXP)**
1	-6.3	-0.38	0.25	0.04	0.09
2	0	-0.02	0.05	0.02	0.04
3	6.3	0.34	0.41	0.04	0.08
4	12.6	0.57	0.67	0.11	0.17

TABLE II. NACA-2414 Results

NACA-2414 Airfoil Results					
Sr. No	**Angle Of attack (α) in degrees**	**Lift Coefficient, CL (NUM)**	**Lift Coefficient, CL (EXP)**	**Drag Coefficient, CD (NUM)**	**Drag Coefficient, CD (EXP)**
1	**-6.3**	**-0.20**	**-0.16**	**0.04**	**0.07**
2	**0**	**0.12**	**0.18**	**0.02**	**0.05**
3	**6.3**	**0.45**	**0.64**	**0.04**	**0.09**
4	**12.6**	**0.62**	**0.85**	**0.10**	**0.18**

The C_L (NUM) and C_L (EXP) for NACA-0012, at four different values of α, are plotted in Fig. 5.

While The C_D (NUM) and C_D (EXP) for NACA-0012, at four different values of α, are plotted in Fig. 6

The C_L (NUM) and C_L (EXP) for NACA-2414, at four different values of α, are plotted in Fig. 7. While The C_D (NUM) and C_D (EXP) for NACA-2414, at four different values of α, are plotted in Fig. 8.

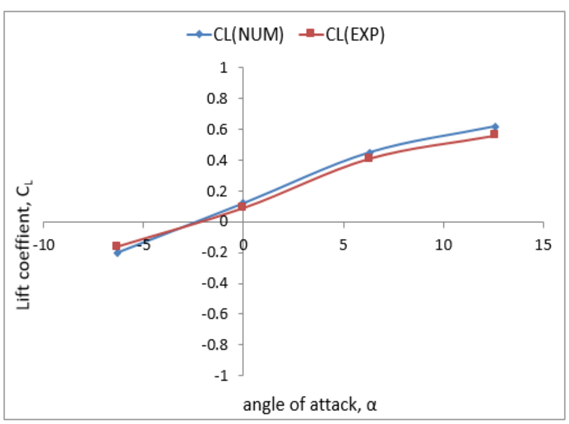

Fig. 5. Numerical and Experimental plots of NACA-0012 Lift coefficient

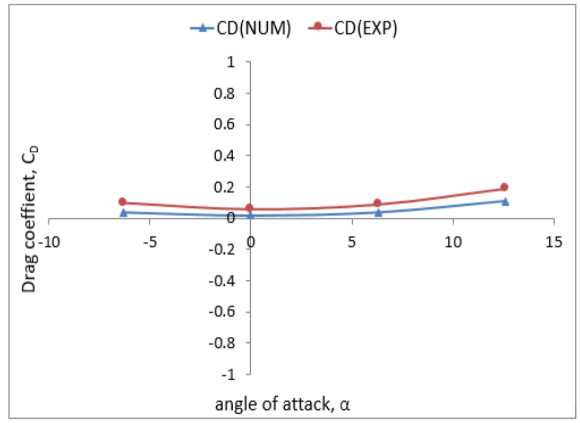

Fig. 6. Numerical and Experimental plots of NACA-0012 Drag coefficient

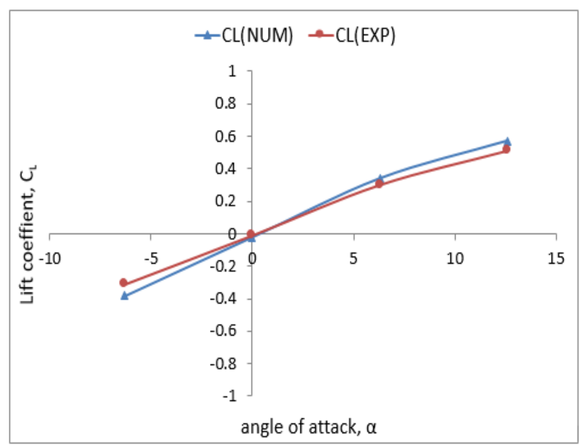

Fig. 7. Numerical and Experimental plots of NACA-2414 Lift coefficient

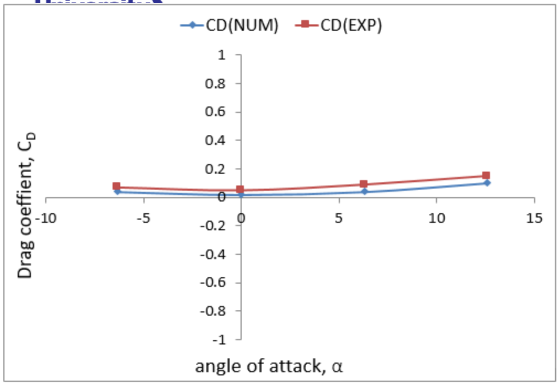

Fig. 8. Numerical and Experimental plots of NACA-2414 Drift coefficient

The behavior of Contour velocity plot across wind tunnel outlet test section shown in Fig. 9. while the Path-lines of air across airfoil in the test section shows in Fig.10. The streamline plot with balls representing the path of streamlines at test section shown in Fig.11. and Eddy Viscosity Contour plots across wind tunnel test section shown in Fig.12.

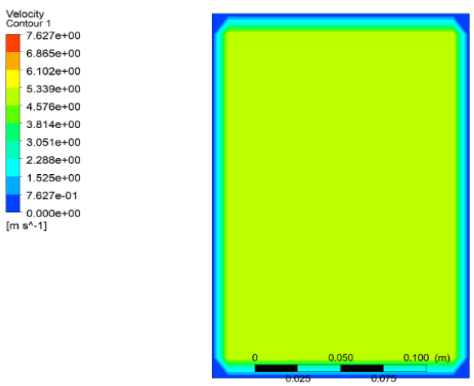

Fig. 9. Contour velocity plot across wind tunnel outlet test section

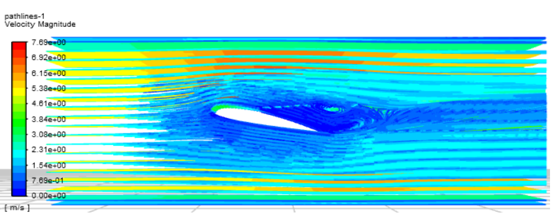

Fig. 10. Path-lines of air across airfoil in the test section

The behavior of Pressure plot across airfoil in at 12.6 degrees angle of attack inside test section is Shown in Fig. 13. and the Velocity plot across airfoil at 12.6 degrees angle of attack inside test section are illustrate in Fig. 14.

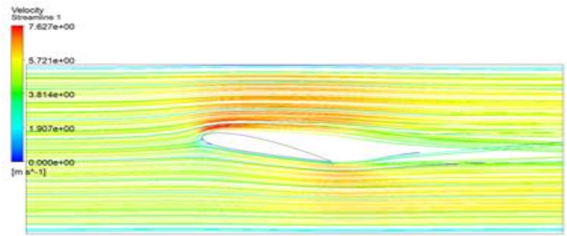

Fig. 11. Streamline plot with balls representing the path of streamlines at test section

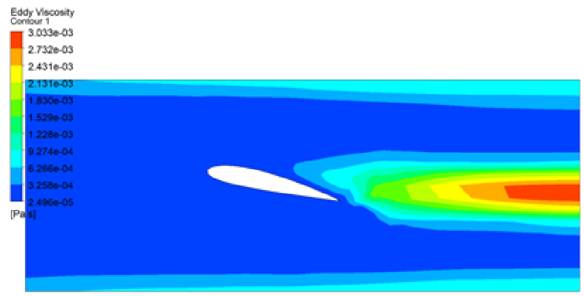

Fig. 12. Eddy Viscosity Contour plots across wind tunnel test section

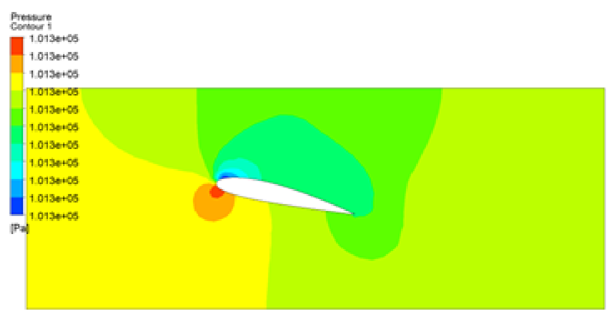

Fig. 13. Pressure plot across airfoil at 12.6 degrees angle of attack inside test section

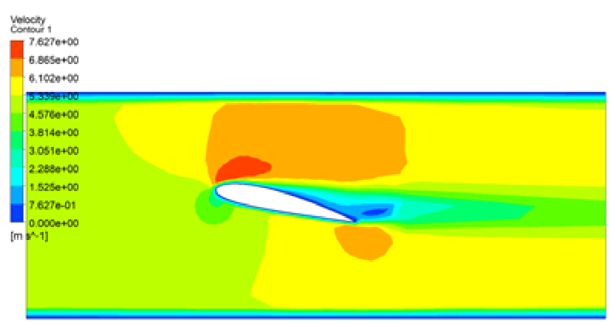

Fig. 14. Velocity plot across airfoil at 12.6 degrees angle of attack inside test section

4. Discussion

The comprehensive analysis presented in this study encompasses both numerical simulations and experimental observations over a range of angles of attack (-6.3 degrees to 12.6 degrees) at a consistent

Reynolds number of 100,000 [15]. The coming discussion discusses the insights obtained from the numerical predictions and experimental results that have been performed in the real world, shedding light on the complex aerodynamic behaviors of NACA-0012 and NACA-2414 airfoils [5].

A major observation is made from the comparison between experimental and numerical values of lift, which shows small differences, where the experimental lift values always lag behind the numerical data at different angles of attack. This discrepancy is due to the experimental setup definitions [16]. The complicate geometry and a very small surface area of the mounting fixture that are not considered in the simulations may be accounted for this minor difference [17]. The perfect model of simulation without these factors leads to highly precise and accurate numerical results [18]. However, friction losses due to the mounting mechanism will lead to some variation in experimental results [19], thus making it important to minimize the losses so that these experimental results become closer to ideal numerical predictions.

The overall validity of the study is reinforced by the small difference observed among the data points. The mean of the two datasets, the numerical and experimental results, happen to be the strength metric against which the performance characteristics of the airfoils in question are defined [11]. Such amalgamation thereby provides a more inclusive analysis while reducing the impact of minor divergences in individual data points.

As the coefficients of lift and drag for NACA-0012 and NACA-2414 under different angles of attack are compared, some really interesting results appear. It is revealed that the lift and drag coefficients are higher for NACA-2414 when subjected to different positive angles of attack, making them conducive for low-speed flight. In the meantime, the symmetrical, thinner shape of NACA-0012 shall prove more effective when expecting high speed scenarios. Interestingly, NACA-2414 is in contrast to preferences in wind turbine blade design, where efficiency at low speeds matters the most [20].

While it can be a useful facility for assessing drag and lift forces, the wind tunnel has some built-in disadvantages. Its limitations to measure only such forces need careful consideration for design engineers. The design of test bodies thus has to be considered very carefully. The size of the body under test must be in-line with the size of the wind tunnel's test section; and the accuracy of results also depends on considering the turbulence intensity from the tunnel walls. Speeding up the airflow must take into account the entry length of the tunnel and is necessary for proper streamlining of the air, which is the key to achieve accurate and reliable results [21].

The viscous effects were reflected in the study and manifest in the slowing of airspeed in the wind tunnel [22]. The resulting turbulence intensity distribution, characterized by features observed near the corners of the tunnel section, reveals another interesting aspect of aerodynamics which must not be overlooked in experimental design. Such effects notwithstanding, the boundary layer thickness was kept quite small owing to the absence of any roughness apart from the smooth galvanized iron and Plexiglass test section. This is yet another reason of success of the experimental setup in keeping controlled aerodynamic conditions.

Observation of streamlines has given a hint of airflow dynamics-since it indicates how particle moves with the airfoil at a given angle of attack. It highlights the angle at which the streamlines are depicted at 12.6 degrees to show the complex airflow in and around the airfoil, which shows quite an important signature concerning the aerodynamics at work around it.

Figures 13 and 14 deal with the pressure and velocity distributions over the airfoil at 12.6 degrees angle of attack. The pressure distribution which had higher values under the tip substantiates the contribution of the element to lift. The lift-drag component is observed through a simultaneous increase of drag with an increase in angle of attack [5].

The highest velocities appear at the upper leading-edge because of lower pressure, confirming the more detailed saliencies provided by velocity distribution [19]. At the same time, it can also be concluded about the regions at the trailing-edge that, on the basis of wake region and vortices, they have lower velocities by some point and, thus, contribute to the complex flow patterns generated by the shape of the airfoil at the trailing-edge.

The key contribution of the study is merging the results from wind tunnel experiments with numerical simulations and comparing it with the existing literature. This work provides a solid basis for designing and testing specific applications for aviation, wind turbines, sports equipment, and highly streamlined transportation vehicles. It connects mathematical theory to real-world applications, laying the groundwork for future advances in aerodynamics and wind tunnel experimentation.

5. Conclusion

This study successfully develops and analyze the subsonic wind tunnel for aerodynamically drag and lift characteristics for two different airfoil models, NACA-0012 and NACA-2414. It combined numerical simulations and wind tunnel experiments to gain comprehensive data on the aerodynamic behavior of the airfoils at different angles of attack. The system was also demonstrated in the construction of wind tunnel prototype galvanizing iron and acrylic material. The airfoil model was experimentally tested for lift and drag coefficients at different angles of attack. The results show close agreement between the numerical simulations with the experimental results thus validating precision in wind tunnel testing. The wind tunnel uses a variable speed centrifugal blower motor and ensured a continuous air flow within the test section. NACA-2414 model demonstrated much higher lift and drag values at positive angles of attack which makes it much feasible for low speed aviation applications. At the same time, NACA-0012 with its symmetrical and thinner shapes is much feasible for use in high-speed applications. This research work also highlighted the importance of friction losses as well as the size of body under consideration compared to wind tunnel size. It also provided a better understanding of the effects of viscus, turbulent distribution, streamline, pressure, and velocity across the airfoils. Even though numerical and experimental data points have slight variations, the designed wind tunnel has generated results comparable with simulations and in the existing literature. This indicates the scope for the future study and design optimization of several airfoil models and their testing results for varied industrial applications including aviation, wind energy, sports, and transportation. The results of the study can also be integrated with pilot-facing electronics that include navigation, communication, data display and controls, electromagnetic interference tests, and electrical circuit protection.

6. Author Contribution

All authors contributed to this research equally.

7. Data Availability

Data will be available upon request.

8. Funding Source

The research was funded by National Grassroot ICT Research Initiative with grant number NGIRI-2023-21414.

9. References

[1] Sor, S., *et al.*, "Development and characterization of a low-cost wind tunnel balance for aerodynamic drag measurements, *European Journal of Physics"*, vol *40*(4), pp. 045002, 2019

[2] Ozcan-Coban, S., *et al.*, "A review on computational fluid dynamics simulation methods for different convective drying applications", *Thermal Science*, vol *27* (1) Part B, pp. 825-842, 2023

[3] İbrahim, G., Comparison of square and curcular sectioned wind tunnel performance, *"The International Journal of Energy and Engineering Sciences"*, vol *6* (2), pp. 50-59, 2021

[4] Abobaker, M., *et al.*, "Numerical Study of Wind-Tunnel Wall Effects on Lift and Drag Characteristics of NACA 0012 Airfoil", *CFD Letters*, *12*. (11), pp. 72-82, 2020

[5] Almeida, O.d., *et al.*, "Low subsonic wind tunnel-Design and construction", *Journal of Aerospace Technology and Management*, vol *10*, 2018

[6] Frechen, F.-B., *et al.*, "Aerodynamic performance of a low-speed wind tunnel", *Water Science and Technology*, vol *50 (4)*, pp. 57-64, 2004

[7] Fang, Y., *et al.*, "Numerical study on heat and flow transfer characteristics in rectangular mini-channel with S-shaped turbulator inserted", *Thermal Science*, pp. 210-210, 2022

[8] Li, Y., *et al.* "*Force measurement system of a low-speed wind tunnel"*, 2009 9th International Conference on Electronic Measurement & Instruments, 2009, pp. 3-302-3-305

[9] Spera, D., "Models of lift and drag coefficients of stalled and unstalled airfoils in wind", *Turbines and Wind Tunnels*, 2008

[10] Li, T., *et al.*, "Numerical investigation of particles turbulent dispersion in channel flow", *Thermal Science*, *16*(5), 5, pp. 1510-1514, 2012

[11] Li, N., "*The methods of drag force measurement in wind tunnels"*, 2013.
[12] Cattafesta, L., *et al.*, "Fundamentals of wind-tunnel design", *Encyclopedia of aerospace engineering*, pp. 1-10, 2010
[13] Centre, G.R., "Models of Lift and Drag Coefficients Stalled and Unstalled Airfoils in Wind", Report, NASA, Cleveland, Ohio, 2008.
[14] AirfoilTools, *NACA Airfoils database*.
[15] Van der Vooren, J., "On drag and lift analysis of transport aircraft from wind tunnel measurements", *Aerospace science and technology*, *12*(4), pp. 337-345, 2008
[16] Baker, J., *et al.*, "Two-dimensional wind tunnel and computational investigation of a microtab modified airfoil", *Journal of Aircraft*, *44*. (2), pp. 563-572, 2007
[17] Chen, J., *et al.*, "A new direct design method of wind turbine airfoils and wind tunnel experiment", *Applied Mathematical Modelling*, *40*(3), pp. 2002-2014, 2016
[18] Chen, Z., *et al.*, "Wind tunnel measurement systems for unsteady aerodynamic forces on bluff bodies, Review and new perspective", *Sensors*, *20*(16), p. 4633, 2020
[19] Fischer, O., *et al.*, "CFD approach to evaluate wind-tunnel and model setup effects on aerodynamic drag and lift for detailed vehicles", 'Report, SAE Technical Paper, 2010.
[20] Pires, O., *et al.* "*Analysis of high Reynolds numbers effects on a wind turbine airfoil using 2D wind tunnel test data"*, Journal of physics: conference series, 2016,753, p. 022047
[21] Post, S.,M. Morris. "*Force balance design for educational wind tunnels"*, ASEE Annual Conference & Exposition, 2010, p. 15.594. 1
[22] Souza, P.V.S.,D. Girardi, "Drag force in wind tunnels: A new method, *Physica A: Statistical Mechanics and its Applications"*, *467*, pp. 120-128, 2017