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Passive Flow Control Over NACA 23018 Airfoil Using Semi-Circular Dimples Across Different Reynolds Numbers

Navid Ibne Newaz Chowdhury, Mohammad Tanveer Ahmed Rafi, Puspita Tasnim and S. M. Taufiq Imrose*

Department of Aeronautical Engineering, Military Institute of Science and Technology, Dhaka-1216, Bangladesh

ABSTRACT

The objective of this research is to examine the influence of surface modification on the aerodynamic performance of a NACA-23018 airfoil. Semi-circular dimples, each measuring 10 mm in diameter, were implemented on the upper surface at 75% of the chord length from the leading edge to mitigate boundary layer detachment. Experimental investigations were performed in a subsonic wind tunnel featuring a test section of 600 × 305 × 300 mm³ across a spectrum of angles of attack. The results showed that the dimpled configuration delayed flow separation compared to the smooth airfoil, leading to improved stall characteristics and enhanced aerodynamic efficiency. It delayed stall from 10° to 18° and achieved a 4.23% increase in lift, up to a 1.4% improvement in lift-to-drag ratio, and up to an 11.1% reduction in drag.

Keywords: Flow separation, NACA-23018, Dimple, Angle of Attack (AoA), Airfoil.

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1. Introduction

The NACA-23018 airfoil is commonly found in various aircraft. Its balance of lift and drag makes it a good choice for light and medium-sized planes. This research aimed to delay flow separation on the NACA-23018 airfoil, which can help improve an aircraft's aerodynamic performance.
Modifying the airfoil surface can effectively delay flow separation[1]. Studies have shown that adding dimples to the top of an airfoil can help delay when the airflow separates[2]. This analysis examines the effect of twelve semi-circular inward dimples, placed at 75% chord on the upper surface of a NACA-23018 airfoil. Two wooden airfoil models were tested: one with a smooth surface and one with dimples. Lift and drag coefficients were measured in a subsonic wind tunnel at Reynolds numbers of 2.0×10^5 and 2.5×10^5 over various angles of attack. The results were analyzed to evaluate how surface modifications influence aerodynamic efficiency. The findings demonstrate that passive flow control can delay flow separation and improve the aerodynamic performance of the NACA 23018 airfoil.
Research indicates that dimples significantly enhance aerodynamic performance by delaying airflow separation. CFD analysis also shows reduced pressure drag and increased lift due to turbulence from semi-circular dimples[3]. The inward dimple design improved lift and reduced drag compared to both the outward dimple and the baseline designs[4]. Dimples on the upper surface of the airfoil significantly delayed flow separation. Placing dimples at 0.75c resulted in a 17% increase in lift and a 6% decrease in drag compared to a smooth airfoil[5]. Placing the dimples close to the trailing edge worked best, especially at distances of 0.7c and 0.9c from the leading edge[6]. Dimples were added to the upper wing surface to improve boundary layer attachment, minimize turbulence, and increase the stall angle. Research works show that dimples on the wing perform better at low Reynolds numbers, especially when positioned near the leading edge and its efficiency depends on factors like size, shape, and location on the wing[7]. Using ANSYS a CFD investigation of the vortex effect on a 3D model of the NACA 0015 airfoil is performed under both dimple and non-dimple conditions and it's been found that C_L with dimples at 0.2c and 0.3c increase lift by 9.9% at 12° stall angle; without dimples, better for 0-5° angles and 10° angle; finally, only 0.3c dimple outperforms the other two modifications[8].
Based on our analysis of the literature, we found that the majority of previous research on dimpled airfoils was largely concerned with 4-digit NACA airfoil sections (such as NACA 2412, NACA 4415, NACA 0015, etc.). This is because they are straightforward and easy to analyze, but they have some limitations regarding maximum lift, stall behavior, and lift-to-drag efficiency. The NACA 5-digit series, features a more precise camber line and thickness distribution, provides greater maximum lift, delay stall, and enhanced aerodynamic efficiency at elevated lift coefficients. However, despite these advantages, relatively little research has examined how 5-digit airfoils perform in modern low-speed applications or how their configurations can be optimized for higher lift-to-drag ratios, especially under different Reynolds numbers and modification, leaving a clear opportunity for further study.

2. Methodology

The NACA-23018 airfoil with a 150mm chord, was designed in SolidWorks. To modify it, twelve semi-circular dimples, each 10 mm in size, were added on the top surface, located at 75% of the width. Two wooden models were made—one smooth and one with the dimples—using a CNC machine. Tests were done in a subsonic open loop wind tunnel. The test area of the wind tunnel is 600 mm*305 mm*300 mm. The speed was set to 20 m/s and 25 m/s, which correspond to Reynolds numbers of 2.0×10^5 and 2.5×10^5, respectively. The models were placed on a three-part balance that was checked and set to zero angle before use. They were then tested at various angles of attack until they reached the stall point. During the tests, lift and drag forces were measured. From these measurements, lift coefficient (C_L), drag coefficient (C_D), and the lift-to-drag ratio (C_L/C_D) were calculated. The results from the smooth model and the dimpled model were then compared to see how the dimples affected airflow, delayed stalling, and improved overall performance. Figure 1 illustrates the sequential methodology followed in this research.

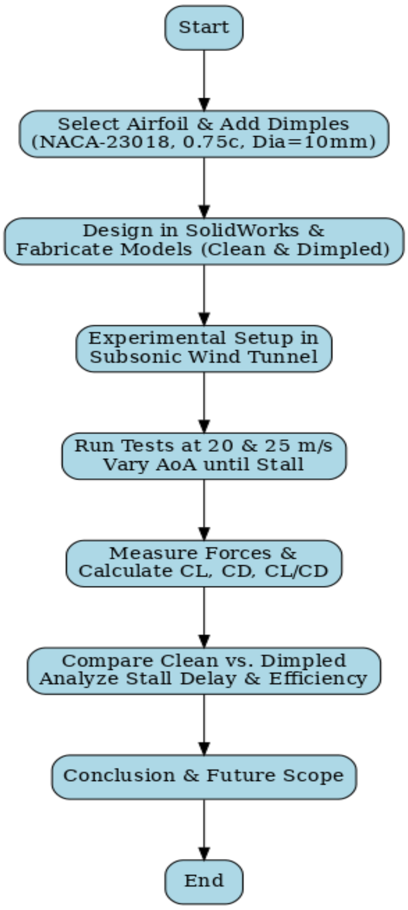

Fig.1: Research workflow overview

2.1 Airfoil Profile Used in Experiment

The NACA (National Advisory Committee for Aeronautics) develops airfoil configurations for aircraft wings. The digits following "NACA" indicate the properties of the airfoil. The five-digit airfoil NACA-23018 is used in this experiment. The initial digit, when multiplied by 3/2, results in the design lift coefficient (C_L) measured in tenths; the following two digits, when divided by 2, represent the location of maximum camber (p) in tenths of chord; and the final two digits signify the maximum thickness (t) expressed as a percentage of chord.

2.2 Numerical Setup

A cambered 2-D NACA-23018 airfoil was chosen as baseline. Its coordinates were generated online, with 30% thickness and 1.8% maximum camber at 15% chord. Using SolidWorks, the airfoil was modeled with a 150 mm chord. Inward dimples were added only on the upper surface to increase lift, decrease drag, and delay flow separation, optimized near the trailing edge.

Table 1: Specifications of the NACA 23018 Airfoil and Semi-Circular Dimple Configuration

Particulars	Specifications
Airfoil series	23018
Chord	150 mm
Type of Dimple	Semi-circular
Diameter of Dimple	10 mm
Location of Dimple	0.75 of Chord (Upper Surface)

Fig.2: 2-D view of NACA-23018 modification details with dimples.

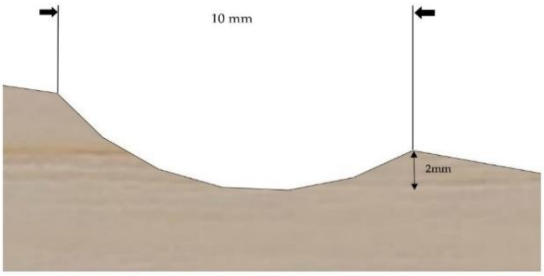

Fig.3: Semi-circular dimple geometry

2.3 Airfoil Model Construction with Dimples

For the experiment, NACA-23018 airfoil models were fabricated from wood using a CNC machine.

Fig.4: Constructed model of NACA-23018 without dimples.

Fig.5: Constructed model of NACA-23018 with dimples.

2.4 Experimental Setup and Procedure

Experimental Tests were conducted in the subsonic wind tunnel rectangular test section in the Aerodynamics Laboratory of Military Institute of Science and Technology.

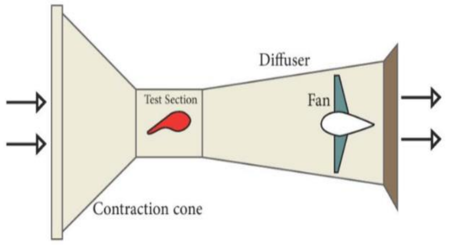

Fig.6: Schematic diagram of wind tunnel test section.

Fig.7: Experimentation of dimpled airfoil using wind tunnel

The NACA-23018 airfoil was first set at zero incidence for calibration and mounted on the three-component balance, with its support shaft passing through the wind tunnel test section. The trailing edge was adjusted to 154.5 mm height, and the balance scale set to zero. Wind velocity was set at 20 m/s and then 25 m/s, while the incidence angle was increased stepwise until stall. Lift and drag coefficients were recorded in tabular form.

2.5 Mathematical Equations Used

The aerodynamic characteristics of a body in a fluid are mainly determined by the lift and drag forces, which can be described using dimensionless coefficients C_L and C_D.
For this, relevant equations have been used to determine the lift and drag co-efficient,

$L = \frac{1}{2} C_L \rho AV^2$ or, $C_L=\frac{2L}{\rho AV2}$ (1)

$D = \frac{1}{2} C_D \rho AV^2$ or, $C_D=\frac{2L}{\rho AV2}$ (2)

where,

L = Lift force (N)
D = Drag force (N)
ρ = Density of the fluid (Kg/m^3)
V = Velocity of the air with respect to the airfoil (m/s)
C_L = Coefficient of lift
C_D = Coefficient of drag

These formulas are essential to aerodynamics since they combine forces for comparison across various situations and designs. Besides, predicting aerodynamic performance and optimizing design parameters require an understanding of such relationships. The coefficients C_L and C_D provide a uniform structure for comparing various flow conditions and geometries under different Reynolds numbers and flow regimes.

3. Result and Discussion

In this paper, the effect of semi-circular dimples on the NACA-23018 airfoil is demonstrated. Experiments were conducted on two surfaces: a clean model and a dimpled (inward) model. The objective was to compare lift coefficient, drag coefficient, and lift-to-drag ratio at different angles of attack for optimal aerodynamic efficiency. Tests were performed at two velocities, 20 m/s and 25 m/s.

3.1 Wind tunnel data

For lift co-efficient, 0° to 25° angle of attack has been used. For drag co-efficient and lift to drag ratio, 0° to 22° has been used. Lift and drag values were obtained using VDAS® software to calculate the lift coefficient, drag coefficient, and lift-to-drag ratio. The resulting data were plotted in Microsoft Excel to compare the two airfoils.

3.2 Lift Co-efficient

The experimental findings of lift co-efficient (C_L) for 20 m/s and 25 m/s velocity are shown in Fig.8 and Fig.9 respectively.

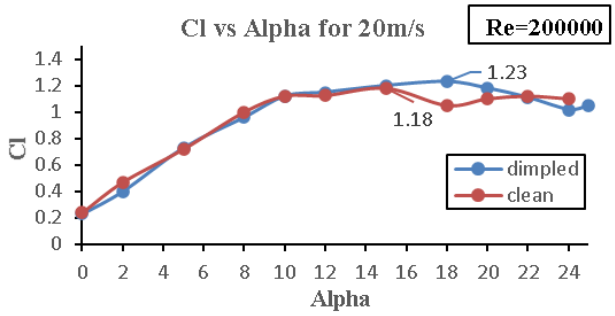

Fig.8: Experimental Values of Lift Co-efficient (C_L) at 20 m/s.

Fig.8 shows that at 20 m/s, the C_L at 0° angle of attack is not zero for either airfoil due to their asymmetry. As the angle of attack increases, C_L rises linearly for both surfaces. Between 0° and 15°, C_L values are nearly identical. For the clean airfoil, C_L decreases at 15°, indicating flow separation, while for the dimpled airfoil, this occurs at 18°. This demonstrates that dimples effectively delay flow separation. Table 2 further shows that the peak C_L for the clean airfoil is 1.18, compared to 1.23 for the dimpled airfoil, indicating that dimples also enhance lift at 20 m/s.

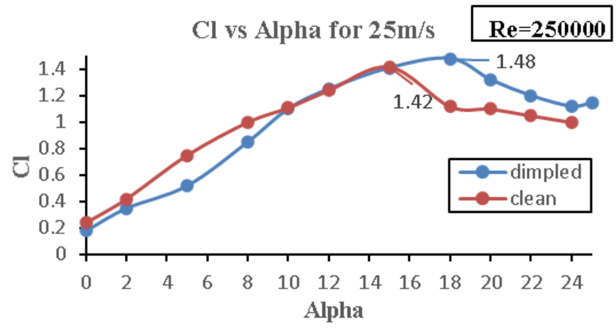

Fig.9: Experimental Values of Lift Co-efficient (C_L) at 25 m/s.

In the case of Fig.9, for 0° to 15° the values of C_L are less in dimpled airfoil compared to clean airfoil. This proves that, from 0° to 15° at 25 m/s, this dimpled airfoil is not aerodynamically good to use. However, the dimples successfully controlled the flow separation in this case also, as it delayed it. On the other hand, the peak value of C_L of both surface airfoil has also increased with the increase of velocity. The peak value of C_L in clean airfoil is 1.42, whereas for dimple airfoil it increased to 1.48.

This case also proves that the dimples can increase lift at 25 m/s than clean airfoil.

3.3 Drag Co-efficient

The experimental findings of drag co-efficient (C_D) for 20 m/s and 25m/s velocity are shown in Fig-8 and Fig-9 respectively.

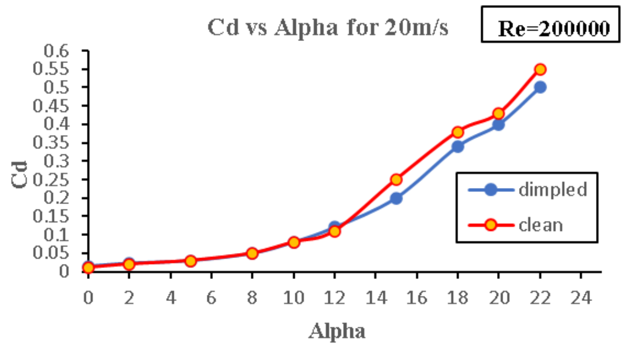

Fig.10: Experimental Values of Drag Co-efficient (Cd) at 20 m/s.

Fig.10 indicates that, at a velocity of 20 meters per second, the drag coefficient (C_D) remains nearly constant from 0° to 12° angle of attack for both surface airfoils. Beyond 14°, the drag coefficient decreases in the dimpled airfoil relative to the clean airfoil. These results demonstrate that the dimpled airfoil exhibits reduced drag compared to the clean airfoil under the tested conditions.

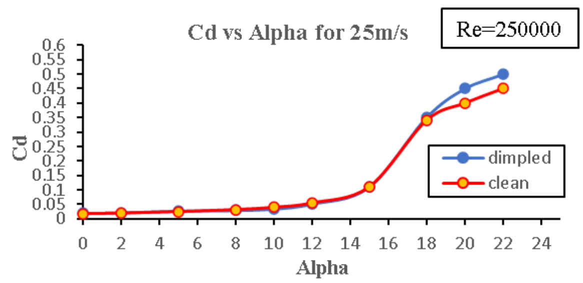

Fig.11: Experimental Values of Drag Co-efficient (C_D) at 25 m/s.

Fig.11 indicates that at 25 m/s, the C_D values remain nearly constant between 0° and 18° angle of attack for both airfoil surfaces. Beyond 19°, the C_D increases for the dimpled airfoil compared to the clean airfoil, contrary to expectations. Therefore, the dimpled surface does not provide effective drag reduction at 25 m/s.

3.4 Lift to drag ratio (C_L/C_D)

The experimental findings of lift to drag ratio (C_L/C_D) for 20 m/s and 25 velocities are shown in Fig-11 and Fig-12 respectively.

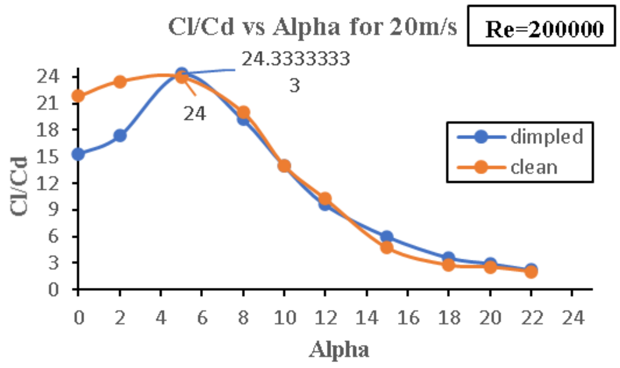

Fig.12: Experimental Values of lift to drag ratio (C_L/C_D) at 20 m/s.

Fig.12 shows that from 0° to 5°, the C_L/C_D ratio increases proportionally with the angle of attack for both airfoil surfaces, though the dimpled airfoil has a lower C_L/C_D than the clean airfoil in this range. At 6°, both surfaces reach their peak C_L/C_D values. Beyond this point, C_L/C_D decreases as the angle of attack increases, but the decline is less pronounced for the dimpled airfoil, indicating a higher CL/CD at greater angles. The peak C_L/C_D for the dimpled airfoil is 24.33, compared to 24 for the clean airfoil. This demonstrates that dimples can improve the lift-to-drag ratio at 20 m/s.

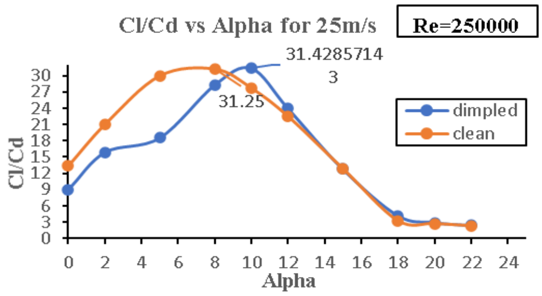

Fig.13: Experimental Values of lift to drag ratio (C_L/C_D) at 25 m/s.

In case of fig-12, the pattern is quite similar to the case of fig-13. But the values of C_L/C_D have increased with the increase of velocity at a fixed AoA. For dimpled airfoil, the peak value of C_L/C_D is almost 31.43, whereas the value is 31.25 for clean airfoil. This proves that with the help of dimples, the lift to drag ratio can also be increased at 25 m/s. The results indicated that a velocity of 20 m/s ($Re = 2.0\times10^5$) produced the best performance. At this speed, the boundary layer was prone to separation, and the dimples created vortices that re-energized the flow, enhanced lift, delayed stall, and improved drag characteristics. At 25 m/s ($Re = 2.5\times10^5$), although lift still increased, the additional disturbances from the dimples caused excessive boundary layer mixing, reduced drag-reduction benefits, and increased drag at higher angles of attack.

3.5 Effect of semi-circular dimple over boundary layer

The position and dimensions of semi-circular dimples significantly influence their impact on the boundary layer and the overall aerodynamic efficiency of an airfoil. Positioned close to the mid-chord area (approximately 40–70% of the chord length), dimples produce controlled vortices that enhance the boundary layer, delay separation, and boost the lift-to-drag ratio, while dimples located near the leading edge frequently induce an early transition to turbulence and elevate drag. The ideal dimple shape is achieved when the dimple diameter is similar to the local boundary-layer thickness, and the depth-to-diameter ratio ranges from 0.02 to 0.08, promoting efficient vortex creation without significant roughness drag. At low flow velocities (low Reynolds numbers), dimples can increase drag because of early transition and thicker boundary layers; however, at moderate to high velocities, they enhance flow attachment, lower pressure drag, postpone stall, and greatly improve aerodynamic efficiency.

4. CONCLUSION

By this research the flow separation of NACA-23018 delayed using semi-circular dimples.

- Semi-circular dimples create turbulence, for this reason flow was attached at higher angles of attack than the non-dimpled airfoil.
- Airfoil with dimples gives about approximately 4.23% increased C_L, 0.6% increased C_L/C_D and 11.1% decreased C_D at velocity 20 ms^{-1}.
- Airfoil with dimples gives about approximately 4.23% increased C_L, 1.4% increased C_L/C_D and 9.1% decreased C_D at velocity 25 ms^{-1}.

4.1 Limitations

This study is subject to several limitations. The experimental design incorporated only two Reynolds numbers, 2.0×10^5 and 2.5×10^5, which restricts the generalizability of the findings to other flow regimes. The investigation was limited to a single dimple geometry, specifically 10 mm semi-circular dimples positioned at 75 percent of the chord on the upper surface. Variations in dimple size, shape, or placement may yield different aerodynamic outcomes. The airfoil models were constructed from wood, a material that does not replicate the aerodynamic characteristics of standard aircraft materials such as composites or metals. The dimensions of the wind tunnel test section may have introduced blockage and wall interference effects. The use of an open-loop subsonic wind tunnel could have influenced flow quality and turbulence, potentially affecting measurement precision. Measurement uncertainties associated with the force balance system were not quantified. The analysis was confined to a two-dimensional airfoil section and did not account for three-dimensional phenomena, including tip vortices. Furthermore, the scope of the study was restricted to subsonic flow, excluding transonic and turbulent flow conditions.

4.2 Future scope

- Further study can be done by putting semi-circular dimples on the lower surface of NACA-23018.
- Only 10 mm diameter dimples are used in this research which can be extended to some other different diameter semi-circular dimples.
- Semi-circular dimples can be located at other positions of the chord from leading edge.

5. ACKOWLEDGEMENT

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7. NOMENCLATURE

Symbol	*Meaning*	*Unit*
AoA	Angle of Attack	Degree (°)
C_L	Coefficient of Lift	Dimensionless
C_D	Coefficient of Drag	Dimensionless
Alpha	Angle of Attack	Degree (°)
R_e	Reynolds Number	Dimensionless