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Evaluating Extendable Turbulators for Airfoil Performance Optimization Across Flight Regimes Using Computational Fluid Dynamics

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ABSTRACT

Commercial aviation faces ongoing pressure to improve fuel efficiency. Turbulators, which are small dimple or fin-like devices mounted on aircraft wings, are known to delay flow separation and reduce stall risk by energizing the boundary layer at high angles of attack and low air speeds. However, at cruise altitude, where the Reynolds number is naturally high and the airflow is already turbulent, turbulators provide negligible aerodynamic benefits while increasing drag and reducing fuel efficiency. This study investigates whether extendable turbulators, which are specifically meant to deploy only during specific phases of flight, could improve aerodynamic efficiency and potentially reduce fuel consumption in commercial aviation. Using two-dimensional Computational Fluid Dynamics (CFD) simulations conducted in ANSYS Fluent, four NACA airfoil geometries (NACA 0012, 2412, 4412, and 6412) were evaluated under two flight conditions: takeoff (12.5° angle of attack, 463 kph) and cruise (5° angle of attack, 850 kph), each with and without a leading-edge turbulator. Results demonstrate that at cruise conditions, turbulators increased drag by an average of 83% while providing negligible lift improvement, substantially reducing aerodynamic efficiency. During high-angle-of-attack conditions, turbulators increased drag while producing flow features consistent with boundary-layer energization and delayed separation. These findings support the feasibility of extendable turbulators as a practical design solution to preserve stall safety benefits while eliminating the drag penalty during cruise flight.

Keywords: turbulators; vortex generators; airfoil aerodynamics; computational fluid dynamics; boundary layer; flow separation; fuel efficiency; NACA airfoil

INTRODUCTION

Commercial aviation faces constant pressure to improve fuel efficiency, and as global air travel only gets more accessible, environmental regulations tighten (1). One promising area of research is turbulators, the small dimple-shaped devices that are often placed on the planes' wings (Figure 1). Their main purpose is to energize the boundary layer by generating streamwise vortices that mix higher-energy freestream air with slower-moving near-wall flow.

However, the turbulators provide negligible aerodynamic benefit during most phases of commercial flight (3, 6). The specific instances when the flight needs them is during takeoff or low air speeds, and at high angles of attack (specifically when the Reynolds number is lower). At cruise altitude, on the other hand, the aircraft is flying at high Reynolds numbers, meaning that

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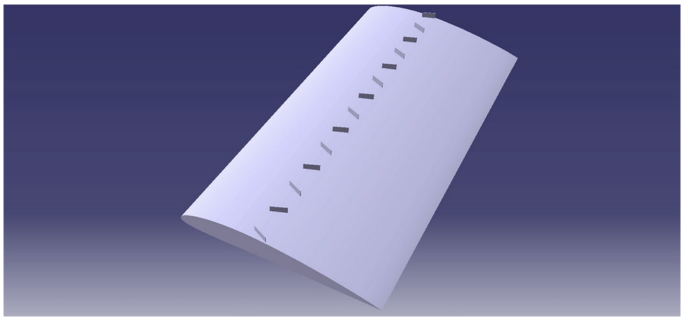

Figure 1. *Photograph of fin-type vortex generators mounted in a row on the upper surface of a swept wing, near the leading edge to energize the boundary layer.*

the airflow is naturally turbulent (2, 3, 4). This means that the turbulators primarily contribute additional drag while providing limited aerodynamic benefit under cruise conditions (3).

During these takeoff or low-air speed conditions, stalling is one of the many aerodynamic risks that an aircraft can encounter. One highly used and researched design feature that can delay or even fully stop this, is the turbulator, known also as a vortex generator. They are small, dimple or fin-like structures on the airfoil itself that manipulate the airflow, allowing the aircraft to maintain lift in challenging flight conditions. Specifically, stall occurs when the angle of attack of an airplane, the angle between incoming flow and the chord line of the airfoil, grows too high. This means that the airflow on the upper part of the airfoil must travel farther and decelerates as it moves toward the trailing edge, that is, the end of the airfoil. This is, in essence, flow separation.

The repercussion of this is that lift is reduced and pressure distribution takes a dramatic change. Stalling can potentially lead to extremely dangerous consequences, such as a loss in altitude and compromised flight safety. When the airflow detaches from the surface of the airfoil, the low-pressure surface weakens, and the lift force drops suddenly. A useful way to visualize this is to imagine air traveling up a spherical surface. When traveling up the first half, it accelerates. However, as it moves past the highest point, it experiences a strong pressure gradient and the flow slows down. If it slows too much, it can begin to move backward relative to the airfoil, "peeling" off the surface. This creates turbulent wake regions that produce significantly less lift. To prevent this, engineers developed turbulators, or vortex generators. They are devices that create small vortices in the airflow that mix high-energy air from outside the boundary layer with the slower-moving air near the wing surface, essentially increasing the energy of the air. This allows the airflow to remain attached to the airfoil for a longer distance. This delays flow separation and reduces the chance of stall happening by increasing the stall angle (Figure 2). As demonstrated with golf ball dimples, flow separation is greatly decreased or delayed when a turbulator is present on the surface (5). Unfortunately, this benefit comes with a trade-off. While turbulators are highly efficient at improving boundary-layer stability, they introduce high amounts of operational drag, highly reducing the fuel efficiency (5). At cruise altitude, the aircraft already operates at much higher speeds and Reynolds numbers, meaning the air is naturally turbulent and energetic (4). In these conditions, the boundary layer typically stays attached, even in the presence of turbulators. As a result, the devices provide extremely little aerodynamic benefit during cruise while still increasing drag, rendering them aerodynamically counterproductive during high-speed cruise flight (3).

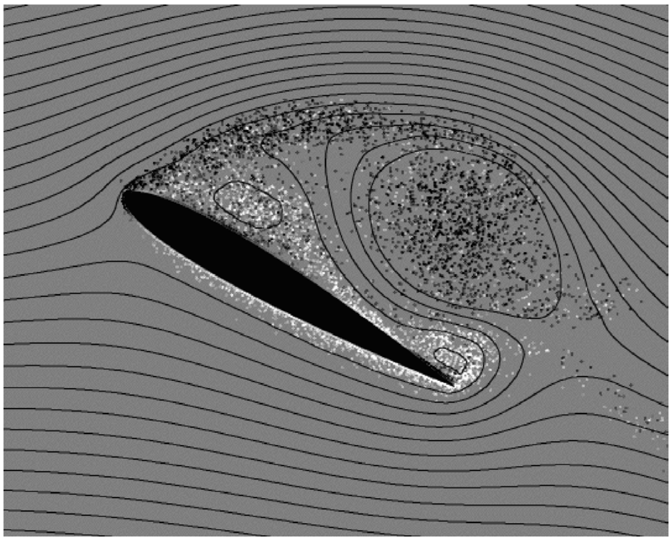

Figure 2. *Streamline visualization of airflow over an airfoil at a high post-stall angle of attack, showing reversed flow and a large turbulent separation region.*

This research investigates if there is a place for extendable turbulators in commercial aviation: devices that would deploy during only specific phases of flight. Using Computational Fluid Dynamics (CFD) simulations in ANSYS, the research compares baseline airfoils with various turbulator types, and finds the effect on the fuel efficiency of different airfoils and planes. It is hypothesized that deployable vortex generators extended only during low-speed, high-angle of attack phases of flight, such as takeoff and landing, will greatly improve the aerodynamic efficiency of the airplane by reducing unnecessary drag at cruise conditions that is associated with permanent vortex generators (3, 6).

METHODS AND MATERIALS

This study employed a two-dimensional steady-state Reynolds-Averaged Navier-Stokes (RANS) computational approach, in which each simulation was treated as an independent test case with conditions varied parametrically across airfoil geometry, angle of attack, freestream velocity, and turbulator presence. In this project, ANSYS Fluid Flow (Fluent) was used to compare and contrast the drag at different altitudes with different airfoils and compare that with the presence of turbulators in those same models. NACA was used as a database for the airfoils, from which the four most used/common airfoils were used in the study (7). Those are the NACA 4412, 2412, 0012, and 6412. These airfoils are commonly used in aircraft design. Additionally, it is assumed that at 463 kph (250 knots) is the representative takeoff condition, or the takeoff angle, where the angle of attack is 12.5 degrees (average is 10-15 degrees) (8). At cruise altitude, the angle of attack is 5 degrees (average is from 2 to 8 degrees), and the speed of the airfoil relative to air is 850 kmh, which is the average for many aircraft (9). These numbers were chosen as they are often used as common average speeds and angles in modern airplanes. Then, the lift and drag are analyzed, as well as calculating the fuel efficiency of having turbulators up for the entire flight versus having it up for parts of the flight where it is actually needed.

To first get the coordinate files for these airfoils, the NACA airfoil database was referenced to find them. The data file was then copied, which has the coordinates for the airfoil. A common issue encountered when importing airfoil coordinates is that the curve edges do not connect in ANSYS Design Modeler. Adjust the coordinates such that the end of the airfoil's y values match up, creating a closed curve. This will ensure any of the issues are avoided. The coordinates were then reformatted into an XYZ format. Since this is a 2D analysis, the Z is always 0. It is very important to note that the airfoil is imported in chunks: the top half the airfoil and the bottom half. The text coordinates were split into two text files, and imported in chunks in Ansys Design Modeler.

Fluent Flow was opened and the Design Modeler was accessed to construct the geometry. A rectangle was created with a height of 30 meters and a width of 15 meters. This served as the fluid domain for the simulation. The domain material was changed from solid to fluid. The coordinate file previously created containing the coordinates of the airfoil was then imported into Ansys. Following this, a 3D curve was created. The airfoil's coordinates were then imported into this 3D curve. This step was then repeated for the bottom half of the airfoil, creating a surface. The boolean tool was then used to remove the airfoil from the fluid surface that was created previously. The final step in creating the normal geometry for an airfoil would be to rotate it along the Z axis, to create significant lift (Figure 3). By using the body transformation tool, the airfoil was rotated by -5 or -12.5 degrees across the Z-axis to simulate an angle of attack.

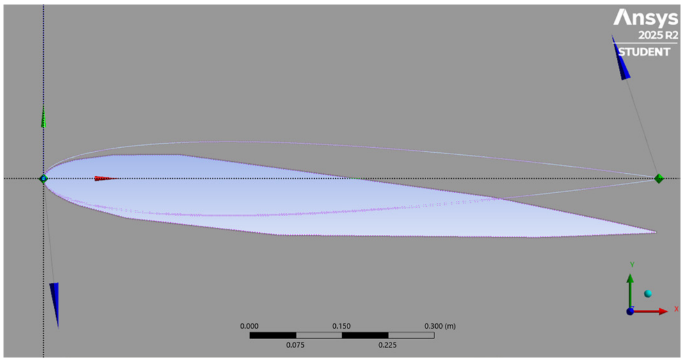

Figure 3. *Basic airfoil in Ansys Fluent with length of 1 meter, and an angle of attack of 5 degrees.*

Finally, when turbulators are needed, more is needed to model the airfoil. To add a turbulator, a simple formula was used. Since the chord length of each airfoil is exactly 1 meter, the turbulator location can be estimated. The x-coordinate where the turbulator is placed is 10% of the chord length, or 0.1 meters. A circle with radius 0.015 meters was created and placed at exactly x = 0.1 meters. This is consistent with experimental and computational vortex generator studies that demonstrated this leading-edge region to be effective for boundary-layer energization (6). A circular cross section of radius 0.015m (1.5% of chord) was intended as a simplified representation of a turbulator rather than an exact reproduction of a commercial vortex generator design.

The Y-coordinate of the turbulator center was taken from the coordinate file at x = 0.1 m. Now, it is important to understand that the turbulator is currently improperly placed, since the airfoil was rotated. The placement was corrected using a trigonometric transformation to account for the airfoil rotation.

When meshing, the default element size is very high, around 2.3 meters. However, to make the simulation as accurate as possible, the element size was decreased to 0.1 meters, so that the results are a true representation of what is actually happening. In the solver setup tab, within the viscous section, the standard k-epsilon (2 eqn) turbulence model was selected. This model is one of the most widely used RANS formulations of industrial CFD, offering robust performance for fully turbulent, attached external flows (10). In the inlet boundary conditions, the inlet velocity was set to either 236.1 m/s (cruise) or 128.1 m/s (takeoff).

The first speed is the cruise altitude speed, and the second is the takeoff speed. Since the experiment is at atmospheric pressure, the gauge pressure was set to 0 Pa. No slip condition was used. Two report definitions were created, for lift and for the drag coefficient. Something that is often overlooked is the residuals. Usually, the absolute criteria of the residuals is set as 0.001. However, this can negatively impact the results that are extracted. This means that anytime a result is within 0.001 of the last result, the simulation stops, even if the iterations are set high. So, this was set to 0.000001 (1e-06), to improve the accuracy of the results and to ensure full convergence of results.

It is important to make sure that the iterations are set to around 1500, to ensure that the simulation is fully converged before iterations run out. Lift and drag coefficients were extracted using ANSYS Fluent's built-in force report monitors. In each 2D simulation, the reference area was defined as the chord length multiplied by a unit span of 1m, consistent with standard 2D per-unit-span-convention. The reference length was set to 1m (chord length), and dynamic pressure was computed from the specific inlet velocity and a standard sea-level air density of 1.225 kg/m^3. Convergence was confirmed by residual decay to the specified tolerance of 1×10^{-6}. This concludes the methodology to conduct the CFD simulations and evaluate the aerodynamic effects of turbulators.

RESULTS AND DISCUSSION

After conducting this research to all airfoils, under different angles of attack, relative air speeds, and with and without turbulators, the results were obtained.

To reiterate how the study was conducted, the lift and drag was compared across 4 different airfoils, extracted from the NACA database: NACA 4412, 2412, 0012, and 6412. These airfoils were then analyzed under two flight conditions; first is takeoff, which means high angle of attack and low relative air speed; second is cruise altitude, which includes a high velocity of air relative to the airfoil and a low angle of attack. Then, each condition was tested with and without a turbulator. This yielded a dataset of 32 test cases.

The dataset was then normalized for easier readability, the highest number in the lift and drag columns being the denominator. For easier comparison across conditions, the results were normalized and are presented in Table 1.

Table 1. *Normalized table shown with all lift and drag values.*

Airfoil Name	Angle of Attack	Speed (alt)	Normalized Coefficient of Lift	Normalized Coefficient of Drag	Turbulator
#4412	*5 degrees*	850 kph	0.858	0.059	Yes
#2412	*5 degrees*	850 kph	0.696	0.053	Yes
#0012	*5 degrees*	850 kph	0.355	0.045	Yes
#6412	*5 degrees*	850 kph	0.974	0.051	Yes
#4412	*5 degrees*	850 kph	0.855	0.036	No
#2412	*5 degrees*	850 kph	0.672	0.029	No
#0012	*5 degrees*	850 kph	0.444	0.023	No
#6412	*5 degrees*	850 kph	1	0.039	No

Continued Table 1. *Normalized table shown with all lift and drag values.*

Airfoil Name	Angle of Attack	Speed (alt)	Normalized Coefficient of Lift	Normalized Coefficient of Drag	Turbulator
#4412	12.5 degrees	**463 kph**	0.238	0.064	Yes
#2412	12.5 degrees	**463 kph**	0.235	0.059	Yes
#0012	12.5 degrees	**463 kph**	0.15	0.047	Yes
#6412	12.5 degrees	**463 kph**	0.364	0.034	Yes
#4412	12.5 degrees	**463 kph**	0.256	0.011	No
#2412	12.5 degrees	**463 kph**	0.362	0.032	No
#0012	12.5 degrees	**463 kph**	0.315	0.019	No
#6412	12.5 degrees	**463 kph**	0.458	0.026	No

Under cruise conditions, most airfoils produced high lift with a moderate or low drag when there were no turbulators present. Cruise conditions consisted of a relative air speed of 850 kph, and an angle of attack of 5 degrees. The airfoils showed strong aerodynamic efficiency. The NACA 4412 without a turbulator produced a normalized lift of 0.855 with a drag of 0.036, while the NACA 2412, without a turbulator, produced a normalized lift of 0.672 and a drag of 0.029. Additionally, the symmetric NACA 0012 produced a lift of only 0.444 but an efficient drag of 0.023, reflecting its lower camber but efficient drag characteristics (Figure 4).

However, when turbulators were introduced to these same airfoils in cruise conditions, an almost unchanged lift but a significant increase in drag was noted (Figure 5). For example, the NACA 4412, with a turbulator, increased only slightly in lift from 0.855 to 0.858, but drag rose from 0.036 to 0.059. This shows the high inefficiency of airfoils with turbulators, representing roughly a 60% increase in drag. Similarly, the NACA 2412 had a significant increase in drag from 0.029 to 0.054, as well as for the NACA 0012, where drag increased from 0.023 to 0.045. Across the airfoils, adding turbulators increased drag by approximately 83% (Figure 6).

Now, airfoils under the high-angle of attack conditions were analyzed. The second test condition represents a low-speed, high-lift scenario, such as takeoff or climb. Without turbulators, several airfoils generated relatively strong lift with low drag. The NACA 4412 produced 0.256 normalized lift and only 0.011 drag, whereas the NACA 2412 produced the highest lift among the baseline cases, producing 0.458 (Figure 7).

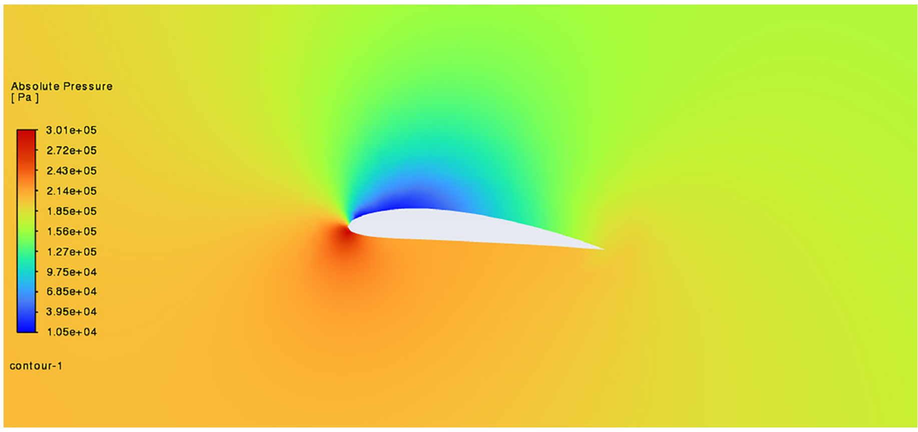

Figure 4. *Absolute pressure contour (Pa) for the NACA 4412 airfoil at 5 degrees angle of attack and at 850 kph, cruise conditions, without turbulator. The pressure differential between the lower (high-pressure) and upper (low-pressure) surfaces confirms lift generation under fully attached flow.*

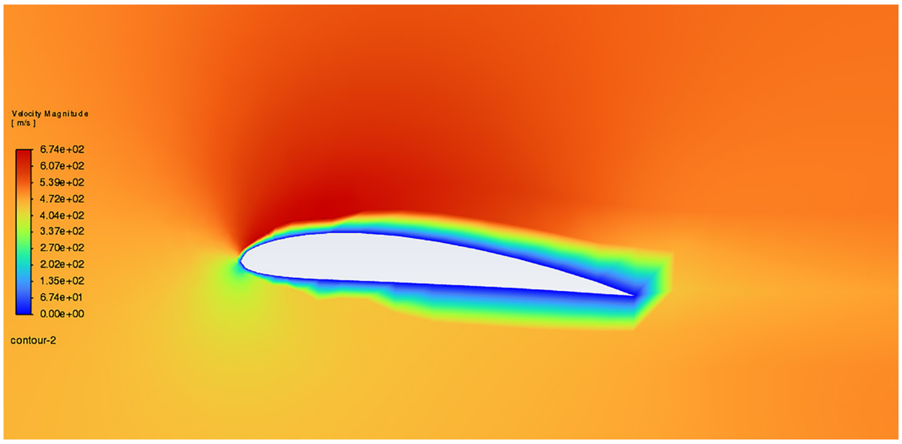

Figure 5. *Velocity magnitude contour (m/s) for the NACA 4412 at 5 degrees angle of attack and 850 kph, cruise conditions, without turbulator. The accelerated flow region over the suction surface and undisturbed wake confirm attached boundary-layer behavior.*

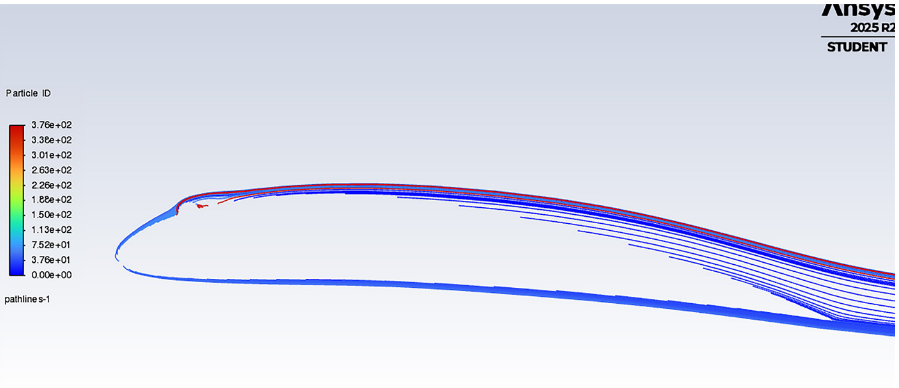

Figure 6. *Particle pathlines (colored by velocity magnitude, m/s) for the NACA 6412 at 5 degrees angle of attack with turbulator at 850 kph. The local disruption of streamlines downstream of the turbulator protrusion illustrates the drag producing wake region generated even under fully attached cruise conditions.*

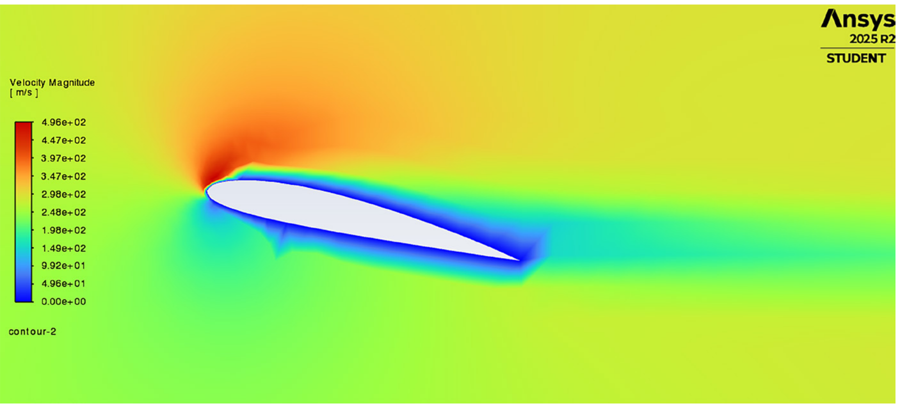

Figure 7. *Velocity magnitude contour of the NACA 2412 at 12.5 degrees at 463 kph without turbulator, takeoff conditions. The boundary layer and increased velocity on the leading edge of the airfoil shows clear lift generation.*

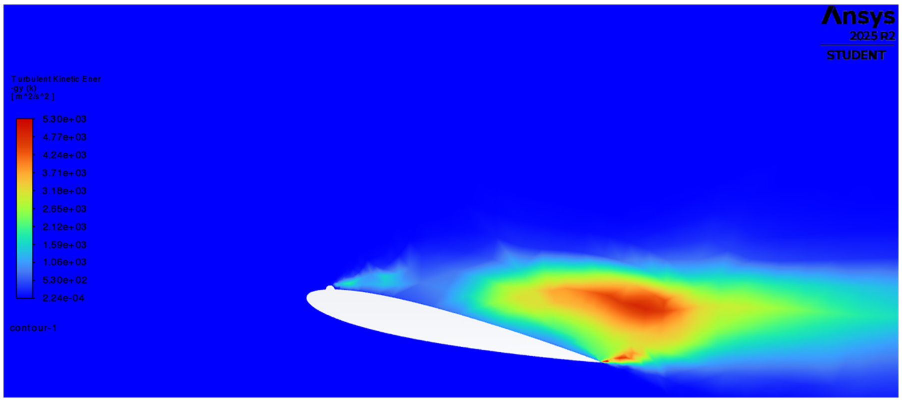

Figure 8. *Turbulent kinetic energy contour (m^2/s^2) for the NACA 0012 airfoil with turbulator at 12.5 degrees angle of attack and 463 kph, takeoff conditions. The concentrated region of elevated turbulent kinetic energy immediately downstream of the turbulator protrusion illustrates the boundary-layer energization mechanism that delays flow separation at high angles of attack.*

However, when turbulators were introduced, the drag increased substantially. The NACA 4412 rose from 0.011 to 0.064, while lift slightly decreased from 0.256 to 0.238. Large drag increases occurred in the NACA 2412 and 0012 airfoils. It is important to note that while turbulators may be seemingly very inefficient here, they are aerodynamically beneficial at this point in the flight, because they help prevent flow separation and subsequent stall. The turbulator is used to create vortices and energize the air such that flow separation does not happen. However, this is not applicable to airfoils at cruise altitude, since airflow is already naturally turbulent due to the high Reynolds number, so the boundary layer already has enough energy to remain attached (Figure 8).

When comparing between turbulator and non-turbulator cases, note that the effectiveness of turbulators heavily relies on the situation. During cruise conditions, turbulators consistently increased drag while providing negligible lift improvements. For example, the NACA 4412 increased in drag from 0.036 to 0.059 with almost no lift improvement. This means that turbulators reduce aerodynamic efficiency of high speed, cruise altitude flight.

In high angle of attack conditions, however, turbulators still increase drag, but it provides a primary benefit. By preventing flow separation, the stall margin of the airfoil can be increased. Even when normalized lift values decrease slightly, the airflow remains attached across the airfoil surface.

The findings are consistent with prior research on turbulators. Research has demonstrated that turbulators in the leading edge region (10-20% chord) are effective at energizing the boundary layer and delaying the flow separation at low Reynolds numbers (6). At cruise conditions, additional turbulence introduced by turbulators yields negligible lift benefit with sustaining elevated drag (3, 10). The standard k-epsilon model used in this study is well-validated for fully turbulent attached flows but is known to underperform under strong adverse pressure gradients near stall (10), which represents a modeling limitation when interpreting the high-angle-of-attack results.

CONCLUSION

This study analyzed the aerodynamic effects of turbulators across multiple airfoil geometries and phases of flight using computational fluid dynamics simulations in ANSYS Fluent. By comparing the NACA 4412, 0012, 2412, and 6412, the results clearly demonstrate that the effectiveness of turbulators is highly dependent on flight conditions.

The study does carry limitations that are inherent to the 2D steady-state computational approach. Future research should more clearly address them through performing a three-dimensional CFD analysis which would allow for a deeper understanding of how turbulators affect lift and drag and more accurately model turbulators, which are generally three-dimensional figures. Though this study used basic dimple turbulators that are highly simplified, future studies should also use physically representative turbulator geometries that are established through three-dimensional designs available. While drag reduction is generally associated with improved fuel economy, this study did not directly model fuel burn or aircraft mission performance. In addition, future studies should investigate a wider study of turbulator sizes and geometries to determine the sensitivity of the results to device dimensions. Finally, it is important that future studies control for angle of attack and freestream velocity independently, to isolate the contribution of each variable, a confound that the present two-condition design was not able to address. During cruise conditions, introducing a turbulator significantly increased drag while providing minimal lift benefit, ultimately reducing aerodynamic efficiency and worsening fuel economy. During high-angle-of-attack situations, like takeoff or climb, the aerodynamic role of the turbulators becomes significant. Even though drag increases, it is necessary to keep the aircraft from stalling.

Overall, the results indicate that turbulators provide only situational aerodynamic benefits rather than universally improving performance. Their main advantage comes at high-angle-of-attack conditions, whereas they reduce fuel efficiency in high-speed cruise. However, these findings suggest a promising direction for future aircraft design: extendable turbulators. During times when stalling is a possibility, the turbulators can be extended as usual, only applying when boundary-layer energization is beneficial, such as during takeoff, climb, or landing. During cruise, the devices could retract into the wing surface, eliminating the additional drag they produce. This aircraft system would increase fuel efficiency while still maintaining the safety and stall-resistance benefits of vortex generators.

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CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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