INTERNATIONAL MULTI DISCIPLINARY JOURNAL FOR RESEARCH & DEVELOPMENT
eISSN 2394-6334 Impact factor: 7,854 Volume 12, issue 12 (2025)

FLOW SEPARATION SUPPRESSION ON AERODYNAMIC SURFACES USING PLASMA ACTUATORS: NUMERICAL AND EXPERIMENTAL ANALYSIS

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Abstract: Flow separation on aerodynamic surfaces significantly degrades aerodynamic performance by increasing drag and reducing lift. Active flow control techniques have therefore gained considerable attention as effective solutions for separation suppression. Among these techniques, dielectric barrier discharge (DBD) plasma actuators offer distinct advantages due to their fast response, low power consumption, and absence of moving parts.
This study presents a combined numerical and experimental investigation of flow separation control on an aerodynamic surface using plasma actuators. Numerical simulations are performed using Reynolds-Averaged Navier–Stokes (RANS) and Large Eddy Simulation (LES) approaches to capture both mean flow characteristics and unsteady flow structures. Experimental validation is conducted in a low-speed wind tunnel using Particle Image Velocimetry (PIV) to obtain detailed velocity fields.
The numerical results show good agreement with PIV measurements in terms of velocity distribution and separation point location. The application of plasma actuation leads to a noticeable delay in flow separation and a reduction in the drag coefficient. The findings confirm the effectiveness of plasma actuators as an active flow control strategy and demonstrate the importance of coupling CFD simulations with experimental verification for accurate flow prediction.
Keywords: Plasma actuator; Flow separation control; Boundary layer; RANS; LES; Particle Image Velocimetry; Drag reduction

1. Introduction

Flow separation remains one of the most critical challenges in aerodynamics, as it leads to increased aerodynamic drag, loss of lift, and reduced efficiency of aerodynamic systems. Separation commonly occurs when the boundary layer encounters an adverse pressure gradient, causing the near-wall flow to decelerate and detach from the surface. Controlling or delaying this phenomenon is essential for improving the performance of aircraft wings, turbine blades, wind energy systems, and various other aerodynamic applications.

Conventional passive flow control methods, such as vortex generators, surface roughness elements, and geometric modifications, have been widely used to mitigate flow separation. However, these approaches are typically optimized for specific operating conditions and lack adaptability under varying flow regimes. In contrast, active flow control techniques offer greater flexibility by allowing external energy input to manipulate the flow field in real time.

Plasma actuators, particularly dielectric barrier discharge (DBD) actuators, have emerged as a promising active flow control technology. These devices generate a localized body force within the boundary layer by ionizing the surrounding air, thereby inducing momentum transfer near the wall. This mechanism enhances boundary layer stability and can effectively suppress or delay flow separation without mechanical components.

Recent advances in computational fluid dynamics (CFD) have enabled detailed numerical analysis of plasma-controlled flows using RANS and LES models. While RANS approaches provide computationally efficient predictions of time-averaged flow behavior, LES offers improved resolution of unsteady flow structures and vortical dynamics. Nevertheless, numerical predictions must be validated through experimental measurements to ensure reliability. Particle Image Velocimetry (PIV) is a powerful non-intrusive technique capable of capturing instantaneous and time-averaged velocity fields, making it well suited for validating plasma actuator simulations.

The objective of this study is to investigate the effectiveness of plasma actuators in suppressing flow separation on an aerodynamic surface through a combined numerical and experimental approach. By comparing RANS and LES results with PIV measurements, this work aims to provide a comprehensive assessment of plasma-based flow control and its impact on aerodynamic performance.

2. Methodology

The flow field is assumed to be incompressible and turbulent. The numerical simulations are based on the three-dimensional incompressible Navier–Stokes equations, which express the conservation of mass and momentum:

Continuity equation:

$$\nabla \cdot u = 0$$

Momentum equation:

$$\rho \left(\partial u/\partial t + u \cdot \nabla u \right) = -\nabla p + \mu \nabla^2 u + F_{plasma}$$

where u is the velocity vector, p is the pressure, ρ is the fluid density, μ is the dynamic viscosity, and Fplasma represents the body force induced by the plasma actuator.

Two turbulence modeling approaches are employed to capture both the mean and unsteady flow characteristics:

• Reynolds-Averaged Navier–Stokes (RANS): The SST k–ω turbulence model is used due to its robust performance in predicting adverse pressure gradient flows and flow separation.

• Large Eddy Simulation (LES): LES is performed using the Wall-Adapting Local Eddy-Viscosity (WALE) subgrid-scale model, which provides improved resolution of near-wall turbulent structures.

The plasma actuator is modeled as a localized body force acting within the near-wall region of the boundary layer. The Suzen–Huang phenomenological model is adopted to represent the time-averaged effect of the dielectric barrier discharge (DBD) plasma actuator.

The plasma-induced body force distribution is expressed as:

$$F_{plasma}(x, y) = F_0 \cdot \exp\left(-x^2/\sigma_x^2 - y^2/\sigma_y^2 \right)$$

where F_0 denotes the maximum force intensity, and σ_x and σ_y define the spatial extent of the plasma force region in the streamwise and wall-normal directions, respectively.

The computational domain consists of an aerodynamic surface placed in a rectangular flow field. A structured mesh is generated with strong refinement near the wall and in the plasma actuator region.

For LES simulations, the near-wall mesh resolution satisfies $y^+ < 1$. A grid independence study is conducted using three mesh densities. The time step is selected based on the Courant–Friedrichs–Lewy (CFL) condition.

The experimental investigation is carried out in a low-speed closed-circuit wind tunnel. The test section provides a uniform inlet velocity with turbulence intensity below 1%. The Reynolds number is defined based on the chord length of the aerodynamic surface.

A dielectric barrier discharge (DBD) plasma actuator is mounted on the aerodynamic surface upstream of the natural separation point. The actuator consists of two asymmetric copper electrodes separated by a dielectric layer.

The actuator operates under sinusoidal AC voltage excitation in the kilohertz frequency range.

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Particle Image Velocimetry (PIV) is employed to measure the velocity field in the boundary layer and flow separation region. A double-pulsed Nd:YAG laser and a high-resolution CCD camera are used. Oil-based tracer particles are introduced into the flow for seeding.

The velocity vectors are obtained using a cross-correlation algorithm, and time-averaged fields are computed from a large number of instantaneous samples.

4. Results

In the baseline case without plasma actuation, a clear flow separation is observed on the aerodynamic surface under the imposed adverse pressure gradient. Both RANS and LES simulations predict the onset of separation at approximately the same streamwise location, although LES captures stronger unsteady flow structures in the separated shear layer.

The velocity contours reveal a significant low-momentum region near the wall, indicating boundary layer detachment. PIV measurements confirm the numerical predictions by showing a pronounced recirculation zone downstream of the separation point. The time-averaged velocity profiles obtained from PIV exhibit a strong velocity deficit close to the surface, which is characteristic of separated flow.

While RANS provides a reasonable prediction of the mean separation location, it underestimates the size of the recirculation zone compared to LES and PIV results. This discrepancy highlights the limitations of steady turbulence models in resolving large-scale unsteady vortical structures.

When plasma actuation is applied, a substantial modification of the near-wall flow is observed. The plasma-induced body force introduces additional momentum into the boundary layer, leading to enhanced flow attachment and delayed separation.

Numerical results demonstrate a downstream shift of the separation point for both RANS and LES simulations. The effect is more pronounced in LES, where plasma actuation significantly weakens the separated shear layer and reduces the size of the recirculation region. Velocity contours show a clear increase in near-wall velocity, indicating boundary layer re-energization.

PIV measurements corroborate these findings, revealing a noticeable reduction in the reversed flow region and a smoother velocity gradient near the surface. The agreement between numerical and experimental velocity fields confirms the validity of the plasma actuator modeling approach.

A quantitative comparison between numerical and experimental results is performed using velocity profiles extracted at several streamwise locations. Both RANS and LES show good agreement with PIV data in the attached flow region. However, in the separated flow region, LES provides a closer match to experimental measurements.

LES captures unsteady vortical structures and turbulent mixing more accurately, resulting in better prediction of velocity fluctuations and reattachment behavior. In contrast, RANS simulations tend to smooth out flow unsteadiness, leading to less accurate representation of separation dynamics.

Despite these differences, RANS remains computationally efficient and suitable for preliminary design studies, while LES is better suited for detailed analysis of plasma-controlled flows.

The impact of plasma actuation on aerodynamic performance is quantified through the drag coefficient. Numerical calculations indicate a noticeable reduction in drag when plasma actuation is applied. The reduction is primarily attributed to delayed separation and a decrease in pressure drag.

LES predicts a larger drag reduction compared to RANS, which is consistent with its improved resolution of flow reattachment and wake dynamics. The trend observed in numerical results is consistent with experimental observations inferred from PIV velocity fields and pressure distribution estimates.

The main findings of the results can be summarized as follows:

- Plasma actuation effectively delays flow separation on the aerodynamic surface.

- Numerical predictions show good agreement with PIV measurements, particularly in velocity distribution and separation location.
- LES provides more accurate representation of unsteady flow structures compared to RANS.
- Plasma actuation leads to a measurable reduction in the drag coefficient, demonstrating its potential for aerodynamic performance enhancement.

5. Discussion

The present study demonstrates that plasma actuators can effectively suppress flow separation on aerodynamic surfaces by re-energizing the near-wall boundary layer. The combined numerical and experimental results provide valuable insight into the physical mechanisms underlying plasma-based active flow control and the relative performance of different modeling approaches.

One of the key observations is the significant delay of the separation point when plasma actuation is applied. This behavior can be attributed to the momentum transfer induced by the plasma-generated body force, which counteracts the adverse pressure gradient responsible for boundary layer detachment. The increased near-wall velocity observed in both LES simulations and PIV measurements confirms that plasma actuation enhances boundary layer stability and promotes flow attachment.

In contrast, LES captures unsteady vortical structures and shear layer dynamics more accurately, leading to improved agreement with experimental PIV data. The ability of LES to resolve transient flow features allows for a more realistic representation of plasma–flow interaction, especially in the separation and reattachment regions. As a result, LES predicts a stronger reduction in flow separation and a greater decrease in drag coefficient compared to RANS. These findings are consistent with previous studies that emphasize the advantages of scale-resolving simulations for active flow control analysis.

Despite its higher computational cost, LES proves to be a valuable tool for understanding the detailed physics of plasma-induced flow modification. However, from an engineering perspective, RANS remains attractive for preliminary design and parametric studies due to its lower computational requirements. The present results suggest that a hybrid approach, in which RANS is used for initial assessment and LES for detailed validation, may offer an optimal balance between accuracy and efficiency.

The experimental PIV measurements play a crucial role in validating the numerical models and confirming the effectiveness of plasma actuation. The close agreement between measured and simulated velocity fields supports the validity of the plasma actuator modeling approach adopted in this study. Minor discrepancies between numerical and experimental results can be attributed to simplifications in the plasma body force model and uncertainties in experimental measurements, such as laser sheet alignment and seeding density variations.

From a practical standpoint, the observed reduction in drag coefficient demonstrates the potential of plasma actuators for aerodynamic performance enhancement. Although the present study focuses on a specific aerodynamic configuration and operating condition, the underlying control mechanism is applicable to a wide range of flow regimes. Future investigations should address actuator optimization, energy efficiency, and scalability to higher Reynolds numbers to further assess the feasibility of plasma actuators for real-world aerodynamic applications.

6. Conclusion

This study investigated the effectiveness of plasma actuators for flow separation suppression on an aerodynamic surface through a combined numerical and experimental approach. Reynolds-Averaged Navier–Stokes (RANS) and Large Eddy Simulation (LES) methods were employed to model the flow behavior, while Particle Image Velocimetry (PIV) measurements were used for experimental validation.

The results demonstrate that plasma actuation significantly enhances boundary layer stability by injecting momentum into the near-wall region, leading to a clear delay in flow separation. Both numerical and experimental findings consistently show improved flow attachment and a reduction in the size of the recirculation zone when plasma actuation is applied. The comparison between CFD predictions and PIV data confirms the reliability of the adopted plasma actuator modeling approach.

A detailed comparison between RANS and LES highlights the advantages of scale-resolving simulations for active flow control analysis. While RANS provides computationally efficient predictions of mean flow characteristics, LES captures unsteady vortical structures and plasma–flow interactions more accurately, resulting in improved agreement with experimental measurements and a stronger predicted reduction in drag coefficient.

Overall, the findings confirm that plasma actuators represent an effective active flow control strategy for mitigating flow separation and improving aerodynamic performance. The combined use of CFD simulations and experimental verification provides a robust framework for analyzing plasma-based flow control systems. Future work will focus on optimizing actuator parameters, assessing energy efficiency, and extending the investigation to higher Reynolds numbers and more complex aerodynamic configurations.

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