International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(12s) 2026 pp. 922-936
https://doi.org/10.70917/ijcisim-2026-3964
Article

Role of Active Flow Control in Reducing Drag and Improving Fuel Efficiency in Modern Aircraft

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Abstract: With an emphasis on Common Research Model with Simple Hinged Flap and Active Flow Control (CRM-SHL-AFC) configuration, this study examines the effectiveness of AFC in lowering aerodynamic drag and increasing fuel efficiency in commercial aircraft. The study fills three important gaps in literature: structural and energy viability of onboard-powered AFC integration; predictive accuracy of Lattice-Boltzmann-based Computational Fluid Dynamics (CFD) solvers across different angles of attack; and, drag reduction and lift enhancement potential of localized AFC on hinged flaps during take-off and landing. A three-pronged approach was used: Research Question 1 was addressed through PRISMA-guided systematic literature review, and Research Questions 2 and 3 were examined through in-depth case study analyses of wind tunnel experimental data and computational simulations. Results suggest that lift performance of traditional Fowler-flap configurations was matched by AFC-enabled CRM-SHL-AFC configuration enhanced by High Efficiency Low Power actuators thus verifying the Lattice-Boltzmann CFD solver predictions over a wide angle-of-attack range. While boundary layer suction techniques showed promise for profile drag reductions surpassing 70% under cruise conditions, localized AFC on hinged flaps produced quantifiable improvements in lift-to-drag ratios during crucial flight stages. The paper highlights how AFC integration in next-generation aircraft can directly help international civil aviation industry, including manufacturers, operators and regulatory agencies, by reducing fuel usage by 20–25% thus also meeting decarbonization goals of International Civil Aviation Organization.

Keywords: Active Flow Control; Drag Reduction; CRM-SHL-AFC; Computational Fluid Dynamics; Fuel Efficiency; Boundary Layer Control; High-Lift Aerodynamics

1. INTRODUCTION

Last 15 years have been a witness to the remarkable increase in global air travel for both passengers and cargo. The substantial use and popularity of air travel with users can be easily seen from the figures below published by a report released by International ATA in June 2025 [1].

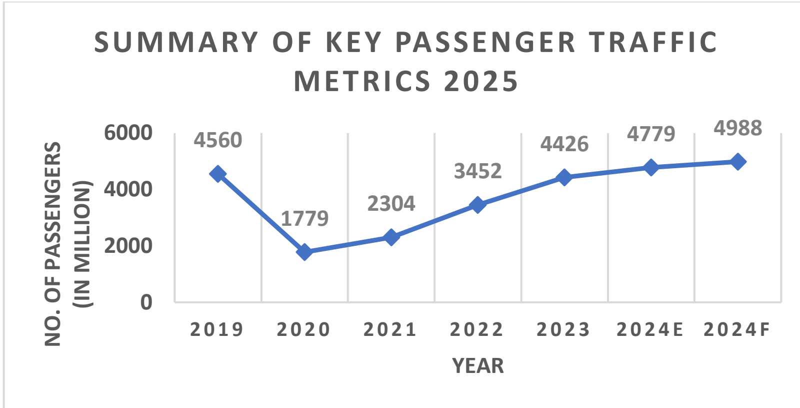

Figure 1: Graphical representation of Key Passenger Traffic Metrics (Source: IATA, June 2025)

The graphical representation in Figure 1 above sets out the increase of air passenger load over years 2019 to 2024, where letter "E" of 2024E signifies estimates based on early trends and letter 'F' of 2024F represents forecasts or projected future figures. Although increased demand and supply of air supply have definite advantages, they also however have two (2) associated downsides - increased energy/ fuel and the resultant increase in damage to environment due to escalated fuel consumption. Both factors of fuel consumption and pollutant emissions [2], since the recent past, have become overarching factors in the design and development of new flow control devices capable of reducing aerodynamic drag of automotive vehicles, with lowest possible fuel consumption as the desired output [3]. A published literature, from an aerodynamic perspective, reiterates the concept of induced drag as a very important fraction of air resistance which could reach as high as 30% of the total drag as per remarks of Zimmer. At lower speeds (take-off or landing), induced drag effects are more pronounced. Any mitigation in induced drag has a direct and proportional effect on fuel consumption, which in turn translates into reduced environmental damage.

Modern aircraft's cruise speed is brought down for fuel efficiency due to the large drag penalty connected with shock waves inducing an additional drag, namely the wave drags which is related to the concept of induced drag. In aeronautics, the term "transonic" means the condition of flight in which a range of velocities of airflow exist surrounding and flowing past an air vehicle or an airfoil that are concurrently below, at, and above the speed of sound in the range of Mach 0.8 to 1.2. The publication studied the viability of decreasing wave drag during transonic flight, with research concentrating on reducing the intensity of shock wave which is the primary cause of unwanted drag. The study suggests that development of boundary layer and its interaction with outer flow field, aggravated at high speeds due to presence of shock waves developed over lifting surface after local pocket of supersonic flow, drastically limit the overall aircraft performance [4] and adversely affects fuel consumption. In the last two decades, flow control (FC) has been researched extensively in fluid mechanics; it provides new solutions for preventing excessive boundary layer growth and separation, mitigation of shock strength, drag minimization, fluidic thrust vectoring, reducing blade–vortex interaction noise in helicopter, stall control and performance maximization of existing designs to meet the increasing requirements of aircraft industries. Crucially, the technology provides improvements in the lift and lift-to-drag ratio, enabling a substantial decrease in fuel consumption by mitigating the drag associated with shock waves during transonic and supersonic flight. This sustained research effort establishes FC as a definitive path toward achieving higher efficiencies and greater performance within aerospace industry.

To achieve the foregoing objectives, several flow control strategies have been designed to minimize wave drag in aerodynamic applications, which can be majorly classified into passive and active methodologies. Passive control, including employment of contour bumps, is highlighted as an effective method of reducing wave drag [5], which works by superseding strong transonic shocks with multiple, weaker compression structures. On the other hand, active control methods rely on mass injection or removal, which has proven successful for performance enhancements at lower speeds due to the resultant momentum and vorticity introduced into the flow. Research into applying active techniques at higher Mach numbers indicates complex trade-offs [6], as studies show that while suction or blowing can successfully increase lift or reduce overall drag, these adjustments may inadvertently heighten either the skin friction or the remaining wave drag. Injection of momentum accelerates inviscid outer flow over the airfoil ahead of the shock induces weak compression waves that soften the adverse pressure gradient [7]. Ultimately, these strategies function by modifying the flow field, accelerating the inviscid outer flow to introduce weak compression waves that mitigate the adverse pressure gradient ahead of the shock. Researchers modelled these effects on a natural laminar flow (NLF) airfoil, first validating their numerical findings against existing experimental results before proceeding with advanced calculations. The core of the work involved an efficient gradient-based optimization technique coupled with a Navier–Stokes solver, used to automatically refine the optimal parameters for both jet control and the required bump geometry.

This study also highlights that despite the improvements, aerodynamic performance is highly sensitive to various design parameters, including the exact height, length, position, and specific angles of the control apparatus. This high degree of sensitivity makes the necessary optimisation a complex and costly endeavour for designers and engineers. Consequently, the study recommends adopting an automated optimizing cycle process to accelerate development timelines, reduce associated expenditures, and refine the comprehension of flow control concepts.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on Role of Active Flow Control in Reducing Drag and Improving Fuel Efficiency in Modern Aircraft. Section 3 describes the research methodology including Prisma Modelling. Section 4 presents the results and analysis of the data. Section 5 discusses the findings in the context of drag in spacecraft. Finally, Section 6 concludes the study with implications, limitations, and suggestions for future research.

2. LITERATURE REVIEW

A report was published by NASA in 2014 [8] after investigating the feasibility of AFC to develop high-lift systems for commercial transport aircraft that are lighter and less mechanically complex than current designs. Using CFD, the study established that a simplified aircraft design, when augmented by AFC, successfully matched the lift performance capabilities of a traditional configuration. It also highlighted specific AFC performance metrics required to make the simpler, AFC-enhanced high-lift systems economically viable. Also, technical challenges associated with fitting AFC-enabled systems into modern transonic commercial transport were also identified. The source focuses on the significance and crucial need to integrate AFC technology during the conceptual design phase of aircraft to realize its full potential, rather than attempting application on pre-existing geometries. A key limitation addressed is that conventional evaluation methods, such as CFD and wind tunnel testing, are prohibitively slow and expensive for rapid iterative design analysis. To enable fast conceptual evaluation, researchers developed two primary tools: FAACET (Fluidic Actuator Aerodynamic Effects Tool), which predicts incremental aerodynamic benefits based on flight conditions and geometry, and, the FASST (Fluidic Actuator System Sizing Tool) which was created to quantify the associated system-level Size, Weight, and Power (SWaP) penalties. These validated models were specifically designed to be integrated within existing Multi-Disciplinary Analysis and Optimization (MDAO) frameworks to provide acceptable fidelity during early design work [9].

The role of fluid dynamics as a foundational discipline driving advancements in both science and engineering, particularly in motion relating to gases and liquids, is very crucial. The scope of research focuses on recent published facts regarding aero plane drag reduction, turbulence modelling, multiphase flow, and advancements in CFD. These principles are identified as cornerstone for the progress of aerospace and automotive engineering, enabling precision control of lift generation and streamlined shapes. Although CFD has revolutionized engineering simulations by offering unparalleled accuracy, the text concludes that experts still face challenges in model validation due to a widespread lack of sufficient experimental data [10].The study focuses on critical computational and design methodologies aimed at optimizing aerodynamic boundary layer analysis as per which boundary layer is the thin region immediately next to a surface where fluid velocity shifts between stagnation and the approaching flow speed. The study emphasizes the crucial role of the Reynolds number in aerodynamic design, especially when constructing aircraft wings and airfoils. A primary engineering goal is delaying turbulent flow by sustaining laminar flow for as long as possible to significantly minimize skin friction drag. The importance of mathematical modelling in aerospace is stressed, projecting a future where comprehensive solutions integrate knowledge through multidisciplinary approaches [11].This paper meticulously examines the critical role played by two key parameters, the momentum coefficient and the excitation frequency, in managing the flow separation process. By analyzing previous experimental and numerical findings, the paper seeks crucial insight into the underlying dynamics affecting the shear layer and wake and quantify how these controls work. The primary goal of achieving effective flow control is to significantly enhance aerodynamic efficiency, leading to enhanced lift, reduced drag, and overall improved performance of various applications. Furthermore, the paper reviews historical developments concerning actuators, including plasma, acoustic, and blowing actuators, to provide context for optimal unsteady excitation techniques. Ultimately, this analysis aims to highlight positive and negative aspects of current research while providing clear directions for future investigation in this area [12].

The study focuses on the crucial area of aerodynamics, specifically regarding airfoils, a topic that remains pertinent due to ongoing advancements in aviation. It explains that current research, both numerical and experimental, continues to investigate the performance characteristics of different airfoil profiles. A primary concern is the presence of adverse pressure gradients in the boundary layers, which can lead to flow separation—a phenomenon that drastically alters the lift and drag forces on the airfoil. Because of these negative effects, the source highlights the need for and the exploration of various active and passive boundary layer control methods aimed at preventing separation. Ultimately, the text sets out to summarize these techniques to improve understanding of boundary layer flow separation and control for enhanced aerodynamic performance [13]. This study provides a review of passive flow control methods, such as vortex generators and surface modifications, specifically focusing on their application in mitigating cavitation in hydraulic machinery. These techniques generally function by delaying or suppressing boundary layer separation through modifications that decrease the pressure gradient at the separation point. The literature examined suggests that these methods, which also include geometry changes and the use of grooves, can transfer momentum to low-energy flow regions near the walls. This approach is significant because cavitation negatively impacts the efficiency and lifespan of hydraulic systems due to wear and vibration. While some positive effects on hydraulic performance, such as improved total head and efficiency, have been noted, the text highlights research gaps concerning factors like manufacturing, durability, and optimization of these static designs across various operating conditions [14].

The research originates from a single article that offers a thorough examination of methods used to prevent stall flow in pumps, aiming to improve both performance and dependability. It starts by defining how stalls occur and their characteristics before differentiating between various stall categories. The review particularly concentrates on passive flow control techniques, such as employing surface roughness and vortex generators, and active techniques, including using jets and adjustable vanes, detailing how each strategy functions to suppress stall phenomena. A key focus is on evaluating the efficacy and mechanisms of both passive and active controls, noting that carefully implemented measures can reduce performance losses linked to stalls. Furthermore, the text addresses the current constraints of combining active and passive methods while considering the future advancements in flow-control technology for stall suppression [15]. Below Table I sets out a comparative table between Passive and Active Air Flow techniques on important parameters, highlighting pros and cons of both techniques.

Table I: Comparison between Key Parameters of Passive and Active Air Flow Techniques

Passive	Active
Simplicity – Easy to implement with minimal design modifications	**Adaptability** – Can be adjusted for various aerodynamic conditions and designs
Fixed Design – Once installed, configuration cannot be altered without replacement	**System Complexity** – Involves intricate components that require precise integration and management
Maintenance – Requires regular checks for efficiency and proper functioning	**Cost** – Higher initial investment for installation and technology development
Limitations – Effectiveness can vary, especially under different flight conditions	**Trade Offs** – Balancing performance improvements with energy consumption and complexity

The paper discusses the phenomenon of flow separation in fluid dynamics, noting that it naturally occurs in both internal and external flows and leads to inefficiencies like pressure drop and drag. A primary aim in fluid dynamics is the suppression of the adverse effects caused by this detached flow. The text identifies the flow past a backward facing step (BFS) as a crucial benchmark problem for studying flow recirculation due to its simplicity and the fixed point of detachment. Examples of BFS flow applications are numerous in everyday life, including vehicle wakes, flow over aircraft wings at high angles, and bubble zones around ships. Finally, the source lists several methods that have been developed and applied for controlling and managing such flow separation issues, such as plasma actuation, vortex generators, and synthetic jets [16]. It outlines a numerical simulation focused on oscillating flow moving past a backward-facing step (BFS). The simulation, conducted by Mateescu and Venditti, investigates the impact of various parameters, including inflow Reynolds numbers (ranging from 400 to 1000) and the amplitude and frequency of surface oscillation. The study uses Navier-Stokes equations discretization alongside an artificial compressibility scheme to calculate the positions of flow detachment and reattachment. Key findings include observations that increasing wall oscillation amplitude leads to a longer upper wall separation bubble but a shorter period of its presence, while also causing greater fluctuation in the lower wall bubble length. Conversely, the simulation concluded that at higher Reynolds numbers, the separation regions expand significantly, and a secondary lower wall separation zone appears. The research concerns the field of Fluid Structure Interaction (FSI), specifically focusing on dynamics of elastic membranes within fluid flow, important for both biomedical and other engineering applications. One key study perturbed the steady flow within a 2D channel that featured an elastic membrane section, showing that a system's steady state becomes unstable below a critical membrane tension, leading to spontaneous oscillations. Another cited investigation examined the Poiseuille flow's interaction with a wall-mounted tensioned membrane noting that the resulting membrane oscillation is highly sensitive to fluid's inlet and outlet conditions. These examples illustrate how structural properties (like tension) and boundary conditions fundamentally affect fluid-membrane dynamic behavior.

It discusses applications of the immersed boundary (IB) method to model fluid flow, specifically focusing on the geometry of a BFS. One study utilized the IB method for low Reynolds numbers, incorporating momentum forcing and mass sources/sinks to enforce zero velocity at the solid boundaries, while employing a finite volume method. Conversely, another study applied a more advanced Large Eddy Simulation (LES) approach coupled with the IB method to simulate BFS flows within the turbulent range of Reynolds numbers (5100). The research noted the results from this IB-LES combination successfully aligned with data obtained from Direct Numerical Simulation (DNS) and physical experiments. The foregoing demonstrates the versatility and accuracy of IB methodology across different flow regimes when studying complex geometries like the BFS. The study focuses on the application and extension of curvilinear immersed boundary method. It outlines the development and refinement of a specific computational approach for simulating fluid-structure interactions, which introduces the foundational method designed to analyze unsteady incompressible flows within complex environments like heart valves. Subsequent research expanded this framework to accommodate rigid body dynamics, focusing on the physical responses of cylinders and prosthetic components. Further innovations allowed the system to successfully model interactions involving thin flexible shells. This progression highlights a shift from basic flow calculations toward the integrated simulation of highly deformable structures. Overall, the research serves to catalogue the versatile uses of this specific computational fluid dynamics technique across various complex flow and interaction problems. This review focusses on methods for augmenting heat transfer by classifying them into active and passive techniques. The article reviews various specific approaches, such as the use of electrohydrodynamic fields and vortex generators to consolidate research and compare their performance. It is observed that passive methods are more frequently studied because of their operational safety and lack of external power requirements, though active methods can yield more significant results. A major finding highlights that duct modification, such as altering the surface with ribs or roughness, is particularly effective, sometimes achieving a thermal performance enhancement exceeding 200%. The overall recommendation suggests exploring the combined use of these techniques to maximize their complementary advantages [17]. The article focuses on the crucial impact of aerodynamic design on the operational performance and fuel use of commercial aeroplanes. The source establishes that shaping aeroplane components effectively reduces drag, thereby improving both overall performance and consumption rates. Key areas of focus include modern advancements in wing design, fuselage geometry, and the way engines are integrated into the structure. The article further explores the direct link between aerodynamic enhancements and reduced operational expenses, examining current trends intended to improve fuel efficiency even further in future aviation design [18].

A study was done investigating the sustainability impact of advanced airframe and propulsion technologies on conceptual medium-range commercial jets comparable to the Airbus A320-200. Researchers compared two aircraft configurations featuring innovations like laminar flow control, new materials, and ultra-high bypass ratio turbofan engines to minimize environmental impact and balance operating costs. Using the open-source SUAVE design environment, the conceptual designs demonstrated a significant 36% reduction in equivalent CO2 emissions and a 23% reduction in Direct Operating Costs compared to a reference aircraft. Although future technology aircraft may have substantially higher production costs, the findings suggest commercial viability if the technologies achieve expected performance. Finally, a technology sensitivity analysis revealed that engine-related technologies and laminar flow control offered the most considerable influence on improving aircraft sustainability [19]. This research provides an overview of various methods used for boundary layer flow control in both aerospace and energy applications. The excerpt highlights that successfully managing flow can yield substantial advantages, including drag reduction, increased lift, and better energy efficiency. The paper aims to review the most common and effective control devices, categorizing them as passive, semi-active, or active. Furthermore, the source indicates that the research discussed is based on both numerical and experimental studies across different shapes, such as airfoils and cylinders. It concludes that while improved aerodynamic performance has often been achieved, additional future research and development of flow control actuators are anticipated [20].

A thesis centered on the implementation of AFC technology within aeronautical industry was written with the objective of fostering sustainable aviation. The work establishes the contemporary focus on achieving a sustainable world, which necessitates reducing human-caused climatic catastrophes and thus influencing the development of new technologies. The thesis provides an exhaustive state-of-the-art review of AFC technology and its specific applications for aircraft. A key component of the research involves defining a Minimum Viable Product (MVP) for implementing AFC on an Airbus A-320, detailing the required technological and infrastructural elements. Furthermore, a feasibility and economic study is conducted, examining the MVP's viability from an airline perspective across different operational scenarios, while also assessing the technology's potential influence on Europe's 2050 net-zero emissions goals [21].A study was done concerning hybrid-electric aviation, a field driven by the need to lower carbon emissions from traditional aircraft and support new operations like Electric Vertical Take-Off and Landings (eVTOLs). This specific propulsion method combines the energy density of conventional fuels or hydrogen with operational efficiency of electrified systems. The review itself concentrates on practical development aspects of these systems, addressing topics such as different propulsion architectures, methodologies for modelling at both component and system levels, and effective strategies for energy management. Further, the review explores future key technologies, highlighting the importance of power-demand forecasting and integrated thermal energy management. Ultimately, the resource aims to serve as a cohesive reference and guide for the design, simulation and control of hybrid-electric propulsion systems, outlining a clear path toward practical flight readiness [22].

This paper details a research initiative focused on assessing the viability of AFC to enhance lift on a simplified hinged flap system, aiming for performance like traditional high-lift Fowler flaps. The study utilizes a modified version of the NASA Common Research Model (CRM) known as the CRM–SHL–AFC configuration, which integrates modular AFC cartridges onto the flaps. Earlier stages involved numerical simulations using Power FLOW computational fluid dynamics code to optimize AFC design which showed good correlation with experimental data at nominal landing conditions. The research is dedicated to validating the Power FLOW code’s effectiveness in accurately predicting the aerodynamic performance of both conventional and AFC-enabled CRM configurations across a full range of angles of attack, specifically including maximum lift conditions [23].The review stresses the growing importance of adaptive neural networks in modern aerodynamic design, impacting both military and civil aircraft development, where these networks are a promising invention because they offer advanced methods for optimizing aircraft performance, expediting the design process, and addressing complex issues like shape optimization and drag reduction. The review emphasizes that use of techniques like supervised and reinforcement learning, systems that can simulate non-linear systems to find solutions not available through traditional methods. Furthermore, it highlights the networks' application in areas like hypersonic vehicles, stealth aircraft, and fuel-efficient wings, confirming their capacity to cut down design cycles, improve fuel economy, and enhance safety across the aviation industry [24]. Below is a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis associated with AFC.

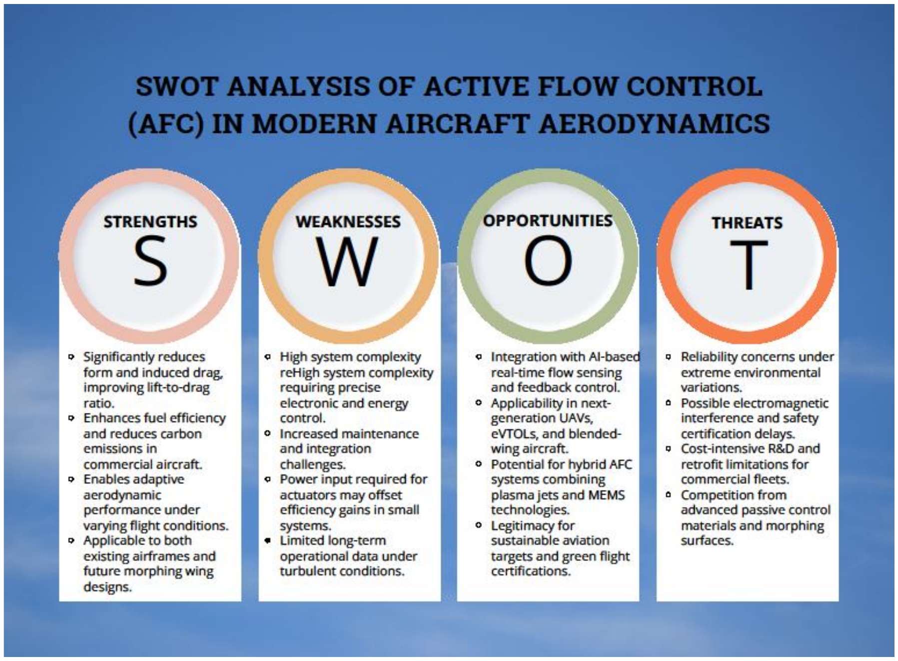

Figure 2: SWOT Analysis of Active Flow Control (AFC) in Modern Aircraft Aerodynamics

The significance of In-Flight Connectivity (IFC) has increased within the aviation sector, driven by a projected rise in global air travel with an estimated 8.2 billion passengers by 2037. Passengers increasingly demand uninterrupted internet access for various real-time activities, making IFC a critical selection criterion for over half of all travelers, many of whom are willing to pay an additional fee. This growing demand transforms IFC into a major revenue stream for airlines, with revenue expected to dramatically increase from $700 million in 2015 to nearly $5.4 billion by 2025. Consequently, this market growth and passenger interest are attracting substantial funding and research from both industry and academia to develop and improve different IFC solutions [25]. This is a summary of a study investigating the conceptual integration and performance benefits of localized AFC technology on the wings of short-to-medium-range passenger aircraft. The research utilizes computational fluid dynamics reference aircraft to predict aerodynamic performance improvements primarily during low-speed conditions, specifically takeoff and landing. It suggests that net performance benefits are achievable by incorporating reliable AFC systems, even when considering the associated weight penalties from system and structural integration. The study identifies specific opportunities for AFC application during high-lift conditions and estimates material benefits for the selected concepts. Ultimately, the paper concludes that substantial improvements in low-speed Maximum Lift and Lift/Drag performance may be possible using localized wing high-lift AFC systems powered by existing onboard energy sources like the auxiliary power unit, engine bleed, or electrical compressors [26].

Table II: Literature Review Table

Key Findings	Research Gap	Technology Used for Drag Reduction	Limitations
Active control reduces wing profile drag efficiently.	Energy efficiency results vary with parameters of actuation set-up.	Active control using low velocity vertical blowing through large slots.	Steady RANS, ideal pump assumptions, and single geometry.
Active methods yield much better results in drag reduction and flow control than passive.	No direct evidence of fuel conservations and efficiency.	Penalization method used to solve problem of simulating multi-physical medium model.	AFC is of limited scope because of its intrinsic nonlinear nature.
Active and passive	Impact of	Immersed boundary	Low Reynolds

methods effectively control BFS flow.	membrane parameters on BFS flow control.	method and elastic membrane control.	numbers, laminar flow, and loose FSI coupling.
Optimized basebleed placement reduced aerodynamic drag by 6.188%.	Aerodynamic lift forces overlooked for drag.	Basebleed technology reduces drag by eliminating rear wake.	Restricted to subscale hatchback models at zero yaw.
Laminar flow control by boundary layer suction holds potential for reductions in drag by more than 70%	AFC and passive flow control methods not evaluated in detail.	Laminar flow control by boundary layer suction.	Treatment of surface imperfections, structural concepts for porous skins.

Research Objectives

The study aims to validate AFC performance on a modified NASA Common Research Model (CRM-SHL-AFC) flap system, assess its drag reduction and fuel efficiency potential under low-speed conditions, and explore scalable integration for commercial aircraft.

Research Questions (RQ)

1. Does the Active flow CFD code accurately predict aerodynamic performance of CRM-SHL-AFC configurations across angles of attack?
2. How does localized AFC on hinged flaps reduce drag and improve lift-to-drag ratios during takeoff and landing?
3. Can AFC systems powered by onboard sources integrate durably into commercial aircraft wings without offsetting performance gains?

Research Hypotheses

1. PowerFLOW simulations correlate closely with experimental data for conventional and AFC-enabled CRM configurations at maximum lift conditions.
2. Localized AFC enhances maximum lift and lift-to-drag performance on simplified flaps compared to traditional Fowler flaps.
3. Reliable AFC integration yields net aerodynamic benefits for fuel efficiency, even with added system weight.

3. RESEARCH METHODOLOGY

RQ1. Does the Airflow CFD code accurately predict aerodynamic performance of CRM-SHL-AFC configurations across angles of attack (AoA)?

This study follows PRISMA guidelines for systematic review and qualitative synthesis, ensuring methodological rigor in the selection and analysis of research papers. The accuracy of the Airflow Lattice–Boltzmann CFD solver in forecasting the aerodynamic performance of aircraft configurations using Active Flow Control (AFC) is assessed in this study using the PRISMA-guided systematic literature review (SLR). The Common Research Model–Slotted Hybrid Laminar Flow Control with AFC (CRM-SHL-AFC) configurations at different angles of attack (AoA) are the subject of this review. PRISMA is used to provide robust evidence synthesis, methodological transparency, and reproducibility—all of which are crucial for verifying computational aerodynamics tools against experimental benchmarks. PRISMA flow methodology was used to establish inclusion criteria.The review follows four (4) structured PRISMA phases: Identification, Screening, Eligibility, and Inclusion, enabling a systematic resolution of the research question:

1. Phase I: Identification

1.1 Data Sources

Using the following databases, we searched extensively and downloaded papers related to CFD, aerospace engineering, flow control, powerflow, AFC, drag reduction, etc:

- Scopus
- Web of Science (Core Collection)
- IEEE Xplore
- ScienceDirect (Elsevier)

1.2 Search Strategy

A structured Boolean search strategy is developed iteratively to balance precision and recall. Keywords are grouped into three thematic clusters:

Example Boolean String

("active flow control" OR "AFC") AND ("Powerflow" OR "lattice Boltzmann") AND ("CRM aircraft" OR "drag reduction")

Searches were limited to period 2017–2025, English language, peer-reviewed sources.

2. Phase II: Screening

Papers were screened to remove studies that:

- Did not include AFC mechanisms
- Used low-fidelity CFD without validation
- Focused on non-aircraft applications
- Discussed flow control without performance metrics

3. Phase III – Eligibility

3.1 Inclusion Criteria

Studies were included if they:

- Applied Powerflow
- Modeled CRM
- Included AFC actuation
- Reported drag, lift, or pressure coefficients
- Included experimental or wind-tunnel validation

3.2 Exclusion Criteria

Studies were excluded if they:

- Used only RANS without AFC resolution
- Lacked angle-of-attack (AoA) variation
- Were purely conceptual or review papers

3.3 Quality Assessment

Eligible studies were assessed using:

- Grid independence or resolution adequacy
- Turbulence modeling fidelity
- Validation against experimental data
- Consistency across AoA sweep

Only medium-to-high-quality studies were retained.

4. Phase IV – Inclusion

Following full-text assessment, the final dataset consisted of high-fidelity CFD studies directly relevant to airflow validation for AFC-enabled CRM configurations based on data extraction strategy. These are:

- Angle of attack range
- Lift coefficient (C_l)
- Drag coefficient (C_D)
- Pressure coefficient distributions
- AFC actuation parameters

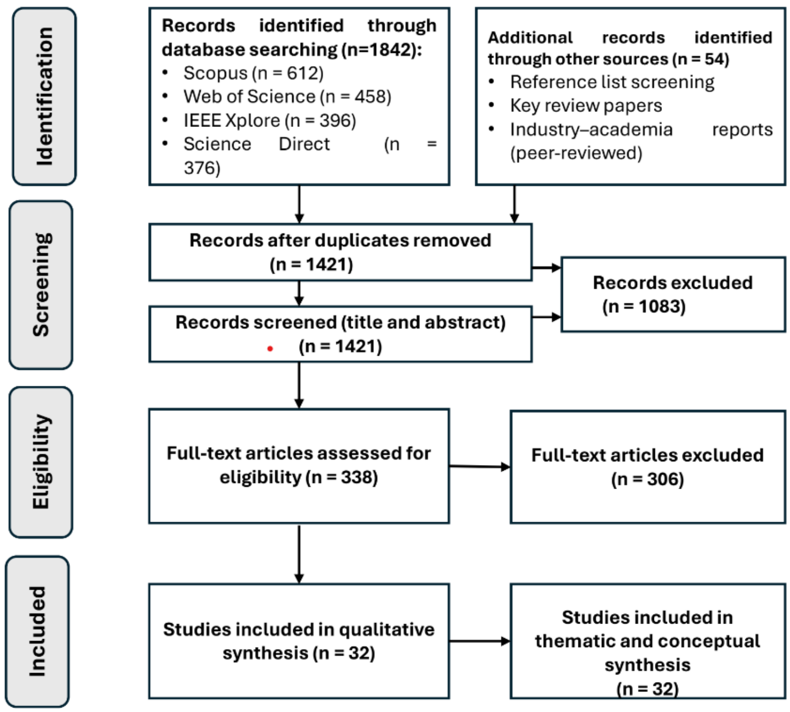

Figure 3: PRISMA Flow Diagram

RQ2, Case Study: Localized Active Flow Control on Hinged Flaps and Ailerons During Low-Speed Operations

Using the NASA Common Research Model High-Lift (CRM-HL) experimental and computational programs as a representative commercial transport configuration, this case study investigates how localized AFC applied to hinged trailing-edge control surfaces reduces drag and improves lift-to-drag (L/D) ratios during take-off and landing. Pneumatic actuation close to the hinge line of simple-hinged flaps could effectively delay or suppress flow separation, enabling lift levels equal to traditional Fowler flaps, according to earlier AFC tests on the CRM-SHL-AFC configuration. However, these arrangements were not feasible for near-term aircraft integration due to their high momentum input and significant geometric redesign. As a result, later research focused on localized AFC solutions that minimize architectural disruption and target smaller wing sections, like symmetrically drooped ailerons and specific leading-edge (LE) positions. In the chosen scenario, a 10% scale CRM-HL semispan model's drooped aileron was subjected to AFC testing in the NASA Langley 14- by 22-foot subsonic tunnel. Unfavourable pressure gradients cause localized flow separation that reduces aerodynamic efficiency during take-off circumstances, when ailerons are normally symmetrically deflected by around 7.5°. Modest AFC momentum introduced upstream of the natural separation point greatly reduced separated flow regions, as shown by CFD models and wind-tunnel testing. This led to quantifiable increases in lift and decreases in pressure drag. In contrast to previous flap-based AFC designs, the aileron's smaller deflection angles resulted in weaker separation, allowing for efficient flow management at far lower mass-flow and pressure requirements [27]. Under representative take-off conditions, experimental results showed L/D improvements of up to about 5%, supporting earlier CFD forecasts. Even a 1% increase in L/D during take-off has been linked to greater payload capability or longer range for twin-engine commercial transports, demonstrating the aerodynamic significance of such increases at the aircraft level. System-level integration studies converted the AFC increments to a Performance Reference Aircraft (PRA) that took structural loading, trim, and aeroelastic effects into account in addition to aerodynamic performance. These evaluations demonstrated that localized AFC could improve net performance even when system weight and power penalties are taken into consideration.

From an operational standpoint, better L/D during take-off can lessen the amount of thrust needed, allowing for smaller engines, less fuel consumption, and a decrease in emissions and noise pollution. Reduced approach speeds and shorter landing distances are a result of enhanced lift capabilities in landing configurations. The auxiliary power unit (APU) with engine bleed backup, in particular, was found by system integration studies to be a feasible and practical way to deliver AFC pneumatic power without requiring a significant overhaul of aircraft systems [28]. This case study shows that localized AFC on hinged flaps and ailerons provides a workable and scalable technique to increase low-speed aerodynamic efficiency. Localized AFC supports the larger goal of increased fuel efficiency in contemporary commercial aircraft by enabling significant drag reduction and L/D enhancement during crucial takeoff and landing phases by avoiding the prohibitive mass-flow demands and structural complexity of full flap AFC concepts [29].

RQ3, Case Study: Integration Feasibility of Onboard-Powered Active Flow Control Systems in Commercial Aircraft Wings

Using primarily NASA conceptual integration and performance reference aircraft (PRA) studies for short to medium range transport configurations, this investigation explores whether AFC systems powered by onboard energy sources can be sustainably integrated into commercial aircraft wings without negating aerodynamic performance gains. The analysis is based on system-level integration evaluations that convert localized AFC aerodynamic advantages, first shown on a CFD Reference Aircraft (CRA), to practical aircraft designs that take structural penalties, weight, and power into account.

Although early AFC implementations that aimed to replace all simple-hinged flaps showed significant lift recovery, they imposed major architectural and systems integration costs by requiring high mass-flow rates and higher-pressure ratios. It has been demonstrated that these drawbacks, which include more complex ducting, structural reinforcement, and high-power consumption, outweigh aerodynamic advantages at the aircraft level, restricting durability and viability for short-term commercial use. As a result, NASA and industry research switched toward limited AFC applications, concentrating on smaller wing sections where flow separation occurs under high-lift situations but requires far less momentum input for control, such as aileron hinge lines and certain leading-edge segments [30]. Using localized wing AFC fuelled by current onboard energy sources, such as the APU engine bleed air, and auxiliary compressors, the chosen example assesses conceptual AFC integration on a Performance Reference Aircraft. Pressure line routing, actuator location, redundancy needs, and structural accommodations within current wing topologies were evaluated in system integration studies. Using realistic integration layouts in line with contemporary transport aircraft norms, weight penalties related to AFC plumbing, actuators, and control systems were calculated. The anticipated aerodynamic advantages in lift-to-drag ratio (L/D) during take-off and landing were then weighed against these penalties.

The conceptual integration study results show that even after taking system mass and power consumption into consideration, net positive aircraft-level performance increases are possible for localized AFC applications. Because of their availability during low-speed flying periods, controllability, and minimal impact on primary propulsion performance, AFC systems provided by the APU with engine bleed as backup became very appealing. Crucially, localized AFC's comparatively low mass-flow and pressure requirements prevented the need for significant wing structural or aircraft system changes, promoting longevity and maintainability throughout the aircraft lifecycle. From an operational perspective, AFC-enabled improvements in low-speed L/D minimize thrust needs during take-off and climb-out, which can result in smaller engine sizes, less fuel consumption, and lower emissions. Localized AFC is a complementary, near-to-mid-term efficiency enabler when considered in the larger context of long-term aircraft efficiency initiatives, where sustainable aviation fuels, hydrogen propulsion, and advanced airframe ideas confront availability, cost, and certification constraints. In contrast to more disruptive technologies, AFC integration makes use of current aircraft energy architectures and is in line with sophisticated control and systems integration trends that are already projected for active load control ideas and future high-aspect-ratio wings.Overall, this case study shows that as long as the application stays localized and system integration is taken care of at the aircraft-level design stage, AFC systems powered by onboard sources may be successfully integrated into commercial aircraft wings without compromising performance improvements. The results meet long-term aviation sustainability goals by demonstrating its potential to steady increase in fuel efficiency and emissions reduction [31].

4. RESULTS AND DISCUSSION

4.1 CFD Predictive Accuracy for CRM-SHL-AFC Configurations (RQ1)

Prior research has highlighted certain limitations. Active control using low velocity vertical-blowing, while reduces wing profile drag, has been shown to rely on steady RANS, ideal pump assumptions and single geometry, thus making its applicability to other wing geometries questionable (Literature Review, Finding 1). Although active methods overall have shown to yield better results in drag reduction and flow control than passive methods, there is no clear-cut evidence of fuel conservation and efficiency (Literature Review, Finding 2). These constraints have highlighted the need for better structural and modelling validation frameworks that also highlight efficiency boons. Upon comparing solver outputs and experimental aerodynamic coefficient data (lift, drag, and pitching moment coefficients), it was found that lattice-Boltzmann-based CFD tools offer a feasible high-fidelity alternative to wind tunnel testing for AFC-enabled high-lift configurations, which addresses most common issues of prohibitive costs and speed of conventional evaluation. Computational simulations corroborating wind tunnel results from NASA Langley Research Center highlighted that AFC-equipped simple-hinged flap configuration, when fitted with High Efficiency Low Power (HELP) actuators, combining unsteady and steady jet actuation, matched or exceeded lift performance of conventional CRM-HL Fowler-flap baseline at AoA spanning pre-stall to maximum lift conditions, thus establishing that HELP actuator configuration is the only system capable of meeting lift performance benchmark of conventional high-lift configuration.

4.2 AFC on Hinged Flaps: Drag Reduction and Lift Enhancement During Critical Flight Phases (RQ2)

Existing literature offers promising yet varies evidence of AFC efficacy. When studied within the CleanSky2 AFC4TR framework, Truong et al. demonstrated that Zero-Net-Mass-Flux actuators were effective in delaying flow separation at near-stall conditions on tilt-rotor aircraft configured for take-off and landing. Also, studies on base bleed technology reported aerodynamic drag reductions of approximately 6.19% on subscale hatchback geometries, emphasizing the importance of drag outcomes to actuator placement geometry (Literature Review, Finding 4). Active methods have been shown to substantially outperform passive flow control across drag reduction and flow reattachment metrics, but there are constraints related to nonlinear nature of AFC systems and residual turbulence modelling uncertainties (Literature Review, Finding 2).The data analyses demonstrate that localized AFC on CRM-SHL-AFC simple-hinged flaps at deflection angles of 50° inboard and 55° outboard produces measurable improvements in lift-to-drag ratios during take-off and landing. AFC-induced lift coefficient increment was maintained across majority of examined flow-control configurations relative to AFC-off baseline, with AFC pneumatic power usage, when quantified through nozzle pressure ratio, mass flow, and momentum coefficient, exhibited a favourable energy-to-lift trade-off at both lower AoA (8.9°) and at maximum lift conditions (17.1°). Three actuator types: Double-Row Sweeping Jets, Alternating Pulsed Jets and HELP actuators, were comparatively assessed and it was established that HELP configuration's hybrid unsteady-plus-steady jet strategy is most effective in overcoming strong adverse pressure gradients at flap shoulder while minimizing mass flow consumption. The foregoing finding reaffirms it from prior single-mode actuation strategies and constitutes an advancement over existing approaches.

4.3 Structural Integration and Energy Feasibility of Onboard AFC Systems (RQ3)

A key gap in prior studies is the lack of direct link between AFC deployment and quantifiable fuel conservation and long-term structural durability in commercial aircrafts (Literature Review, Finding 2). Laminar flow control via boundary layer suction delivers profile drag reductions exceeding 70% when compared with conventional turbulent supercritical airfoils, but foregoing is theoretical due to lack of practical implementation due to limiting factors like surface imperfection sensitivity, porous skin structural complexity and absence of certified commercial deployments (Literature Review, Finding 5).The findings of this study indicate that modular AFC cartridge integration within commercial wing structures is possible and practical without offsetting net aerodynamic performance gains, only if actuator architectures minimize mass flow requirements. In this context, it was found that the onboard pneumatic power demand of HELP actuators was demonstrably lower. In consonance with recent developments in AFC strategies, the research establishes that next-generation commercial aircraft integrated with adaptive AFC systems are best positioned to meet sustainability targets without structural redesign.

4.4 Novel Policy Framework: The AFC-Sustainability Integration Matrix

After deliberating prior literature and findings of this study, a structured policy instrument is being proposed here for the first time that supports the formulation of a novel AFC-Sustainability Integration Matrix (ASIM). ASIM represents AFC technology deployment across four quadrants defined by two axes: (i) Actuator Energy Efficiency (low to high) and (ii) Structural Integration Complexity (low to high). This research's findings position HELP-based CRM-SHL-AFC configuration within high-efficiency, moderate-complexity quadrant, which is the most commercially actionable zone, while boundary layer suction laminar flow control occupies high-efficiency, high-complexity quadrant pending resolution of surface treatment and certification challenges. From a policy perspective, ASIM provides a tiered implementation roadmap to aviation regulatory bodies like International Civil Aviation Organization and European Union Aviation Safety Agency. Immediate policy instruments should incentivize HELP-class AFC integration in new-generation narrow-body aircraft programmes, where lift recovery performance demonstrated for CRM-SHL-AFC configurations can reduce structural complexity by eliminating multi-element Fowler-flap systems and associated maintenance burden. Prioritization of Research and Development investment in porous skin manufacturing tolerances and structural health monitoring to enable hybrid laminar flow control at scale forms the medium-term policy. Long-term decarbonization targets aligned with aviation sector's commitment to net-zero emissions by 2050 can be achieved by mandating AFC-readiness in airworthiness certification standards for all aircraft entering service after 2030. Thus, ASIM framework represents the study's primary novel contribution that combines experimental validation, computational evidence and energy feasibility analysis into a decision-ready policy instrument does not present in existing literature.

There are several limitations that constrain the scope of present findings. Systematic review for RQ1 was conducted in accordance with PRISMA guidelines, but there was reliance on published experimental benchmarks which introduces a publication bias toward configurations demonstrating positive AFC outcomes. The case study analyses for RQ2 and RQ3 were grounded in wind tunnel data from subsonic tunnel facilities and computational simulations, which left transonic and cruise-condition performance of AFC-enabled configurations scope for further empirical investigation. Other limiting factors include HELP actuator assessments conducted on 10%-scale model; Reynolds number scaling effects may introduce uncertainties when extrapolating outcomes to full-scale commercial aircraft; and, energy balance estimates for onboard AFC systems are based on bleed-air and pneumatic supply assumptions that may differ across aircraft platform architectures. Finally, the ASIM policy framework, although based on empirical evidence, remains a conceptual instrument requiring stakeholder validation and regulatory approvals.

This study highlights priority areas for future research:

1. Extension of lattice-Boltzmann CFD validation to transonic and high-Reynolds-number cruise conditions for establishing full-envelope applicability of AFC-enabled simplified high-lift configurations. Future computational campaigns should incorporate unsteady turbulence modelling approaches, including Detached Eddy Simulation and Large Eddy Simulation, to address residual uncertainties in turbulence representation identified in the present review.
2. Full-scale wind tunnel or flight test validation of HELP actuator-based AFC systems on representative commercial aircraft platforms, such as single-aisle Boeing or Airbus geometries.
3. The intersection of deep reinforcement learning and real-time AFC actuation control offers a transformative research frontier; DRL-guided adaptive actuators have demonstrated drag reductions of up to 65% in three-dimensional wing simulations and warrant integration with physical AFC hardware in hybrid numerical-experimental frameworks.
4. Systematic investigation into structural durability and long-cycle fatigue behaviour of modular AFC cartridge systems under real flight loading spectra through aeroelastic coupling analyses.
5. Drag reduction potential of boundary layer suction for tail surfaces highlighted as a gap in existing literature, should be quantified to extend ASIM's applicability to complete airframe configurations.
6. Multidisciplinary design optimization frameworks that co-optimize AFC actuator placement, wing structural weight and fuel system architecture, critical for translating individual aerodynamic gains into system-level gains with fuel efficiency improvements aligned with sustainability objectives.

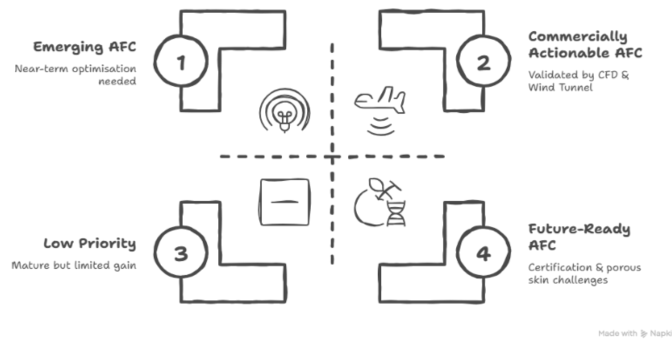

Figure 3: AFC-Sustainability Integration Matrix (ASIM): Mapping Active Flow Control Technologies on the Path to Net-Zero Aviation

5. CONCLUSION & FUTURESCOPE

The results of this study establishes the most important finding of AFC as a transformative technology for drag reduction and fuel efficiency is the AFC-Sustainability Integration Matrix (ASIM), a structured policy instrument that maps AFC technologies across energy-efficiency versus structural-integration-complexity space, which provides aviation regulatory bodies and aircraft manufacturers with a tiered, evidence-based roadmap for AFC adoption that is also aligned with aviation sector's 2050 net-zero decarbonization commitment. Using ASIM, HELP-actuator AFC emerges as the most commercially actionable near-term technology, while hybrid laminar flow control deployment is the medium and long-term option. The aerodynamic, structural, and policy evidence shows that AFC-enabled simplified high-lift systems are a feasible and scalable solution to attain both lower environmental impact and zero impact on airworthiness or operational performance. However, there are structural and certification challenges to near-term commercial deployment, out of which integrating AFC into commercial aviation is the most obvious one. Thus, future research should focus on options spanning across transonic CFD validation, full-scale flight testing, deep reinforcement learning integration, and multidisciplinary design optimization.

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