Variable Geometries of Gas Turbine Engines to Improve Engine Performance

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I. Nomenclature

SFC	=	Specific Fuel Consumption
NOx	=	Nitrogen Oxide
CO	=	Carbon Monoxide
F	=	Thrust of the object
Ve	=	Exhaust velocity of the object
Va	=	Initial velocity of the object
Ae	=	Exhaust Area of the object
ma	=	Mass flow of the air
f	=	Fuel to air ratio
TIT	=	Turbine Inlet Temperature

II. Abstract

This report will focus on variable geometry methods and research currently being utilized or conducted in small-scale turbojet engines with the goal of increasing engine performance and reducing emissions. Understanding the benefits in variable geometry engines versus conventional turbojet or turbofan designs, reducing carbon emissions, learning how to apply this research to large scale engine design and production and to better understand how this technology will spread and change in coming years. Research into variable geometry has concluded that small scale models of these designs are able to greatly increase efficiency and performance in different environments or altitudes. While testing is still taking place to determine the feasibility of large-scale variable geometry engines within 10-20 years. Modern computing and material science will theoretically allow for the efficient production of model engines. If innovations continue at the rate they are at the time of this paper's creation, it is highly probable that traditional turbojet engines will be a relic of the past both in commercial and military flight.

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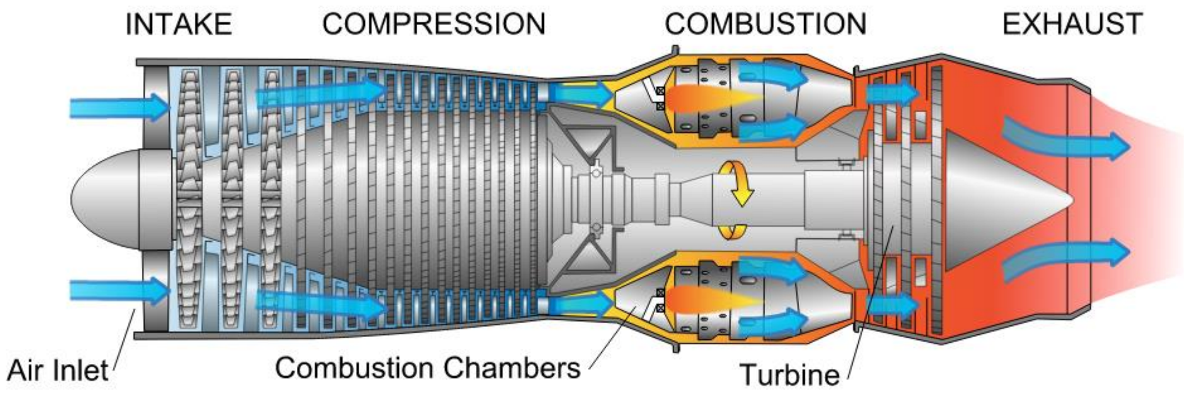


Fig. 1 Diagram of static geometry gas turbine engine

III. Introduction

A. Historical Context and Evolution

The evolution of gas turbine technology represents a continuous quest for greater efficiency and adaptability. Since the mid-20th century, fixed-geometry turbojet engines have been the backbone of aviation, achieving significant milestones in commercial and military flight. However, their inherent limitations, such as inefficiency outside designed operational ranges and high carbon emissions highlighted the need for more flexible systems in the 21st century. Early implementations of variable geometry, such as adjustable nozzles and intakes in military aircraft, paved the way for broader applications. Advancements in computational tools and materials science allowed researchers to envision engines that adapt dynamically to changing conditions, revolutionizing aviation performance and efficiency.

Variable geometry within a turbojet style engine has become a broader definition as technology has evolved. This can refer to changing geometry within the intake, bypass ducts (turbofan aircraft), compressor blade angles, burner and/or nozzle. Such technology allows for greater control over combustion and performance parameters and allows for greater variation in operational conditions for aircraft that would have otherwise been limited by the static geometry of their conventional engines.

Variable nozzle geometry is the most common form of this technology and has been used for decades in everything from high-speed passenger and private jets to military aircraft. This has allowed for greater implementation of afterburner technology, but this is mostly limited to military aircraft with afterburners due to that being the only situation where the nozzle can be implemented effectively.

Variable intake geometry was very common on first generation mach one aircraft. This was used to reduce the intake air speed below mach one to prevent shockwaves within the engine. While effective, modern aircraft have moved to simpler fixed geometry intakes that serve the same purpose more efficiently and simply in comparison.

Most engines that will be analyzed in this report are small test models that implement burner variable geometry. This type of variable geometry is complex and often involves tubular sections that rotate based on the required performance of the engine to open or close expansion chambers within the burner itself. These engines also incorporate other forms of variable geometry, (mostly aft of the burner), to further control combustion parameters for greater efficiency and required thrust.

B. Advantages of Variable Geometry

Variable geometry systems stand apart from conventional engines by their ability to optimize performance in real-time. By modifying intake geometries, compressor blade angles, and nozzle configurations, these engines can maintain efficiency across a wide range of altitudes and speeds. For example, in military applications, variable nozzle geometry enhances afterburner performance. For commercial aviation, variable combustor geometries reduce fuel consumption during low-speed operations, such as taxiing, takeoff and assent.

Standard fixed or static geometry turbojet engines have limited or no ability to change combustion efficiencies. Instead, they are designed to be the most efficient at their intended operating range and altitude. This does mean that they are relatively inefficient outside of these ranges. This is where variable geometry engine technology can be employed. Having the ability to change geometry within the engine itself, especially regarding combustion components, allows for the range of operational efficiency to be far wider than conventional engine design and can allow for greater thrust per unit weight and size due to greater thermal and propulsive efficiencies allowed by this technology.

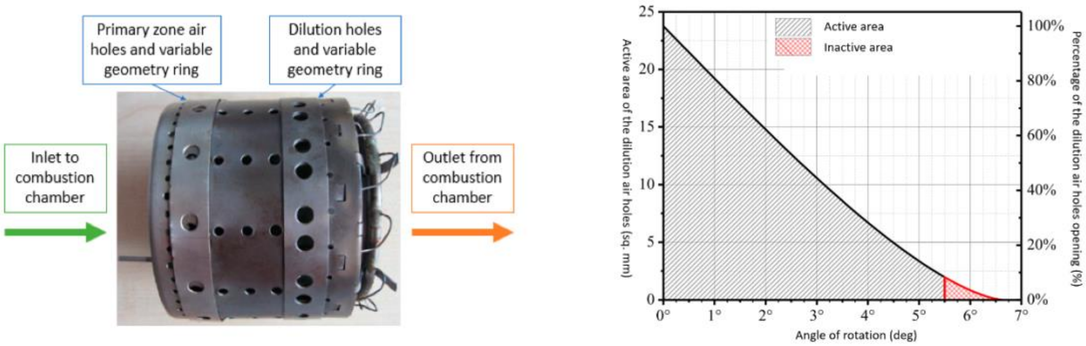
C. Performance

Performance characteristics are vital to choosing engines for aircraft in all fields of aviation. Criteria such as thrust to weight ratios, profile, and SFC among others dictate what engines can be used on an aircraft and what the capabilities of that platform will be. Slower aircraft are on average more fuel efficient and have a larger capacity to carry loads compared to faster aircraft. This can be seen with airliners and military transport aircraft. Lighter and faster aircraft can transport a smaller payload at much greater speeds, however their fuel efficiencies are far lower in comparison.

When describing performance, thrust is the main metric being discussed. Thrust is calculated using:

$$F = \dot{m}_a\big((1+f)V_e - V_a\big) + A_e(P_e - P_a) \quad (1)$$

Variables of this equation and the equations that make up the variables themselves can be manipulated through variable geometry. Starting from the inlet and working towards the exhaust, the density and velocity (and by extension the mass flow rate of air entering the combustion chamber) can be adjusted through variable intake geometry and through compressor blade angle variations. Next, the area of the combustion chamber can be changed to allow for a greater amount of fuel that can be burned without changing the density or velocity of air being pumped into it[3]. Finally, if an afterburner is present or the pressure coming from the combustor is in a choked state, variable geometry in the converging nozzle can allow for more optimal exhaust pressures and by extension greater thrust.



(a) (b)

Fig. 2 Proposed variable geometry combustion chamber: (a) system overview; (b) chart showing air hole area related to percentage of original hole opening

D. Emissions

Engine performance will always be the most important factor in engine design; however, emissions and greater efficiency are a topic of growing concern in the aviation industry. While the overall focus of this push is environmental, greater efficiency is also a focus for engine design to limit unnecessary losses. This can be excess fuel burn, thermal losses, mechanical losses, etc. Regardless of benefits or restrictions, environmental considerations will play a greater role in aviation in the coming decades due to popular demand for decreased emissions worldwide. Instead of having to rely on retrofitting emissions controls on existing aircraft that will limit performance, variable geometry will allow for greater efficiency without the cost of capability. With the introduction of automotive emissions standards in the 1970s, cars became stunted in performance for the next 30 years until the technology for variable components caught up to demands. By pursuing variable geometry systems for aircraft now, the industry will be able to naturally and more effectively implement the growing emissions standards.

E. Conversion to large scale

Currently, variable burner technology is in testing with small scale engines, however, there does not seem to be a limit to size conversion for larger scale engines in the future with current technology and material science. Other forms of variable geometry are currently being used like variable blade angles in compressors and variable geometry of nozzles. Soon, it is likely that public discussion and testing of large engines will take place with multiple variable geometry hot and cold sections. This new data will likely justify even more testing into the topic which will kick off a chain reaction of interest and innovation in the market.

F. Future of variable geometry

The future of variable geometry is very promising and will likely be here sooner than we can predict as the technology to produce such engines is already here. One day, variable geometry engines will be able to propel aircraft faster, higher, longer and with less emissions than ever before. An important note is that the complexity of these engines is not an issue with regard to production as the aforementioned technologies already exist, instead the challenge with these types of engines will be in controlling them. The important complexity in variable geometry is controlling components. Pilots and engineers have used conventional engines for so long due to their components and technology being well understood and safe. One human will not be able to control all components and monitor them in real time. This is where advancements in artificial intelligence will likely come into play, as pilots will be able to instead give AI a target for performance and efficiency, then forget about it and continue to operate the aircraft.

IV. Methodology

A. Overview

This methodology section will detail the systematic approach used to investigate the effects of variable geometries on gas turbine engine performance. This includes a overall review of information and results from patents as well as industry and academic research to draw meaningful conclusions about efficiency, emissions, and scalability of variable geometry. An analysis of the limitations and challenges faced while compiling research on variable geometry will also be considered.

B. Literature Review

This report is built on the study of multiple patents and scientific research papers published by academic institutions. The specified articles were sourced from credible institutions such as MDPI, JSTOR, and ScienceDirect. Search terms included “variable geometries in gas turbine engines,” “enhancing turbine efficiency,” and “combustion optimization in turbojet engines.” These topics were chosen to cast the widest possible net for information and research taking place within the industry.
Key areas of focus included:

1. **Performance Improvement**: Tracking the effects of variable geometry on the performance of gas turbine engines including increased thrust and efficiency.
2. **Experimental Data**: Analyzing research of miniature gas turbines and their performance improvements using variable geometries.
3. **Environmental Impact**: Investigation into the
4. **Scalability Trends**: Identifying challenges and prospects in scaling these designs to commercial and military engines.

C. Limitations and Challenges Addressed

The biggest challenge regarding research on this topic is the lack of relevant resources regarding the turbine. The purpose of variable geometry is to, in part, enable the engine to achieve the stochiometric temperature of the fuel it is burning, in most cases, kerosene. The idea of the variable geometry of a turbine is widely considered outside the realm of possibilities. This is due to the limitations of the material’s properties, specifically thermal resistance and thermal expansion. The turbine, actuators, walls of the turbine, and insulation would need to withstand the temperature rise to 2500 kelvin without failing or interfering with each other. This is currently not possible with the current materials that are available. However, in the future, new materials could be developed with the appropriate properties.

The other underlying issue with variable geometry is its complexity. This is compounded when more than one form of variable geometry is introduced. The basis of this report is to explore the future of this technology and that means the assumption that several, if not all the components mentioned will be used in future designs. Unfortunately, using many or all of these components would overwhelm the capabilities of a human pilot due to the thousands of variables and inputs within the system. Many pilots will likely be uncomfortable with this new technology similar to how many pilots were wary of fly-by-wire or electrically controlled mobility in aircraft starting in earnest in the 1980s. It is the belief of many that similar to the adoption of fly-by-wire technology, AI control systems will become popular as the technology proves itself in action.

V. Results

The results of the literature review show the significant advancement that can be achieved through the implementation of variable geometries in gas turbine engines. The findings are categorized into specific performance metrics, including efficiency improvements, emissions reduction, and scalability potential. Case studies and experimental data further illustrate the benefits of these innovations.

A. Performance Improvements

Variable geometries contribute to advantages in engine performance by adjusting to operational requirements. The adjustments optimize airflow, temperature profiles, and the combustion efficiency, leading to higher thrust-to-weight ratios and Specific Fuel Consumption (SFC) reduction. Engines equipped with variable geometries achieve up to a 20% improvement in thrust per unit weight, especially in supersonic flight conditions and research demonstrates a 15-20% reduction in SFC during mixed operational phases, such as transitions between cruising and climbing.

Experimental testing at the Warsaw University of Technology showed variable geometry combustors can achieve a 47% reduction in fuel consumption. This is attributed to the control of airflow and fuel mixing and a notable improvement in thermal efficiency, with a 35% increase observed under optimized conditions.

The adaptability of these systems allows for performance comparable to multiple fixed-geometry engines. This makes them adaptable across various applications, from subsonic transport to supersonic military jets.

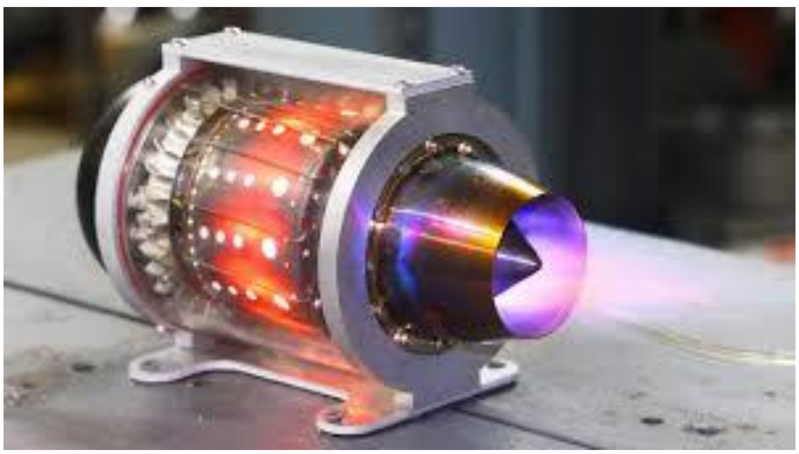


Fig. 3 Miniature gas turbine jet engine.

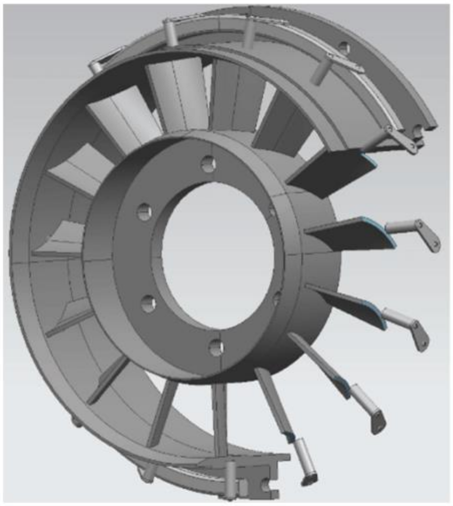
B. Emissions Reduction

One of the most important benefits of variable geometry is its ability to minimize harmful emissions without sacrificing performance. This is achieved by optimizing combustion conditions, resulting in Nitrogen Oxides (NOx), Carbon Monoxide (CO) and Hydrocarbon Emission reduction. Closing dilution holes in the combustion chamber led to an 82% decrease in NO2 emissions during high-power operations. This simulates the adaptability of the engine from cruising to high-speed flight. With conventional engine designs the efficiency of the engine would drop drastically due to the increased demand for thrust being outside the designated cruise operating range.

Figure 3 in the original document shows the impact of variable geometry on NO and NO2 generated in the combustion chambers. These adjustments allow for greater flexibility in meeting environmental regulations while maintaining operational performance.

C. Scalability Potential

The application of variable geometries to larger-scale engines poses unique challenges and opportunities. While current research focuses on small-scale, single variable geometry component experimental models, advancements in materials science and computational modeling suggest scalability is possible even with current technology. Important conclusions that were come to were material restraints in manufacture of such engines and computational validation that the advantages seen in small-scale models would translate to full-scale. While modern high-temperature alloys and thermal resistant composites would not only be necessary, but critical for full scale production, all the necessary materials already exist and can be sourced easily by capable laboratories. Computations have also found that the findings of the original tests will translate almost linearly to large-scale engines meaning the advantages seen in testing will carry onto larger engines.



(a)

(b)

Fig. 5 Researched adjustable turbine nozzle system: (a) 3D model of the variable geometry system; (b) manufactured nozzle with modified geometry (nozzle angle inclination increased +5°).

D. Future Scenarios

As variable geometries transition to large-scale applications; their integration could redefine commercial aviation by:

1. Enabling ultra-efficient long-haul flights with reduced fuel consumption.
2. Supporting supersonic passenger aircraft with engines adaptable to various speed regimes.
3. Revolutionizing power generation turbines by reducing operational costs and emissions.

E. Comparative Analysis

Table 1 illustrates the comparative performance metrics of traditional fixed-geometry engines versus variable geometry engines across key parameters:

Table 1. Comparison between fixed-geometry gas turbine engines vs variable geometry gas turbine engines

Metric	**Fixed-Geometry Engine**	**Variable-Geometry Engine**	**Improvement (%)**
Specific Fuel Consumption	0.8	0.65	18.75
NOx Emissions (g/kWh)	250	45	82
Thrust-to-Weight Ratio	5.0	6.0	20
Operational Range (Mach #)	0.8–2.0	0.5–2.5	N/A

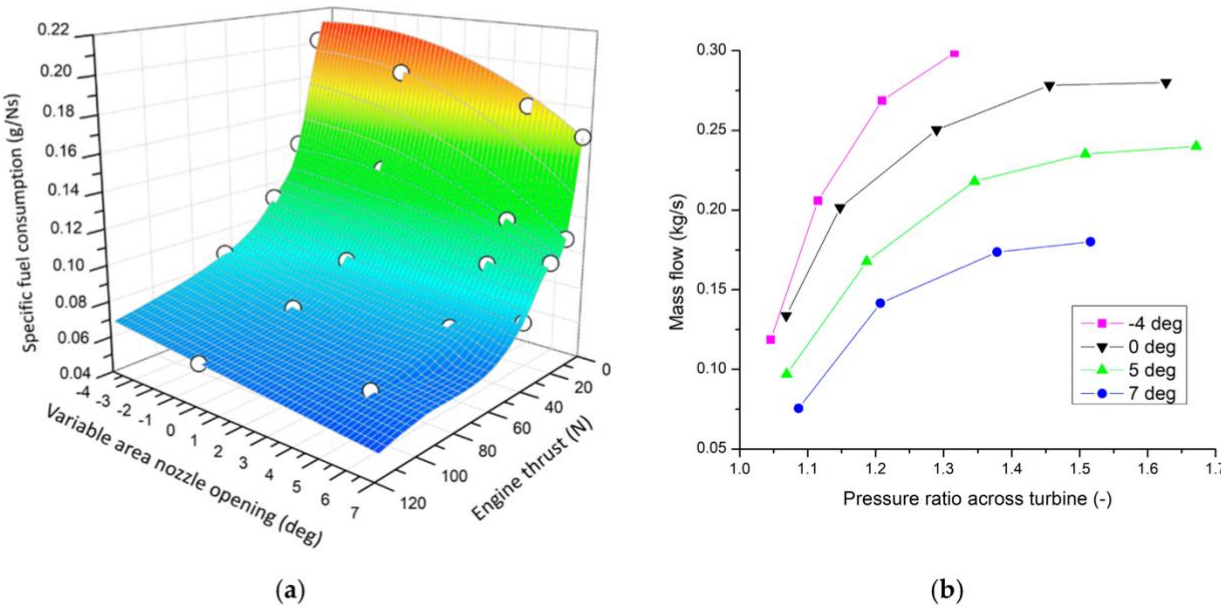


Fig. 4 Turbine variable area nozzle impact on: (a) specific fuel consumption and engine thrust; (b) mass flow and turbine pressure ratio.

This comparison underscores the superior efficiency, adaptability, and environmental benefits of variable geometries.

F. Applications and Environmental Impact

Variable geometry is vital for reducing carbon emissions and improving performance in aviation. Variable geometry, especially within the combustor, turbine, compressor and nozzle of turbine engines allows for more complete combustion of fuel. This is accomplished by adjusting the flow rate and temperature through different means. In summary, greater efficiency is achieved by having greater control over variables within the engine that can be adjusted more accurately to accommodate different environments and operational criteria.

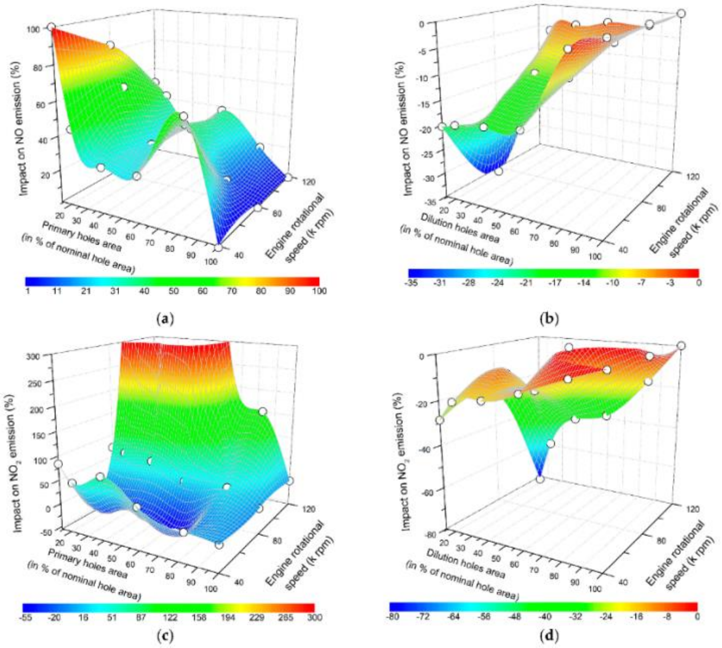


Fig. 6 Combustion chamber variable geometry impact on nitrogen monoxide (NO) and nitrogen dioxide (NO2) generation: **(a)** NO and primary hole impact; **(b)** NO and dilution hole impact; **(c)** NO2 and primary hole impact; **(d)** NO2 and dilution hole impact.

VI. Discussion

A. Key Findings

Adjustable parts in miniature gas turbines, like dynamic combustion chamber expansion make jet-turbine engines eco-friendlier and more efficient. By adjusting the dilution rings of the expansion chamber, researchers in Warsaw saw improvements in how much energy the turbine could produce (thermal efficiency) and reductions in harmful emissions like nitrogen oxides (NOx). Further patents and research have shown the possibility of combining other forms of variable geometry to create further efficiency. Though this is still theoretical in many respects, this demonstrates the possibilities of variable geometry and provides a path to further development within the industry.

B. Increased thermal efficiency

The results indicate that optimizing the effective areas of primary and dilution zone holes provides precise control over the combustion chamber's temperature profile. The most notable improvement in thermal efficiency (up to 35%) was achieved with a 22% reduction in dilution hole area, demonstrating the system's ability to maximize energy extraction from combustion processes. Similarly, turbine nozzle adjustments, particularly at +5° closure, yielded consistent TIT increases and corresponding efficiency gains, particularly at higher rotational speeds.

C. Reducing Emissions

Variable geometry systems proved effective in reducing nitrogen oxide (NOx) emissions. Closing dilution holes meant more air stayed in the primary combustion zone, lowering NO2 emissions by up to 82%. Adjusting the turbine nozzle also helped reduce emissions by controlling how air and fuel mixed and burned.

D. Challenges and Limitations

There are some challenges with the incorporation of variable geometry in full-scale commercial airplanes. These include cost, weight, and complexity.

1) **Complexity:** The use of multiple actuators, sensors, and computers will drastically increase the complexity of the engine. This increase in complexity leads to a greater number of components that could fail.
2) **Cost:** An increase in incomplexity will lead to an increase in cost. A cost-benefit analysis will need to be made whether the increase in cost is worth the increase of

3) **Weight:** While the engine may become smaller dimensionally, the weight of the actuators, sensors, and computers would increase the weight of the engine. A comparison will need to be made whether the increase in power is greater than the increase in weight.

Manufacturers will need to compare the advantages and disadvantages of variable geometry when it comes to these three challenges.

E. Future Directions

Variable geometry engines are both promising and expansive. The advancements in material science and computational modeling can establish large-scale adoption for engine sizing in two decades. Furthermore, trade studies on alternative fuels such as hydrogen and biofuels to name a few, could boost environmental benefits within variable geometry systems.

Once the technology has matured over time, collaboration between academics, industries, and governments should be able to overcome the scalability challenges from small to larger model engines. The transition from experimental to commercial-wide products for widespread use will create a major milestone for related aero companies and engineering.

Proposed developments include more comprehensive Computational Fluid Dynamics (CFD) modeling, exploring hydrogen as a fuel, and fuel–water emulsions for lower combustion temperatures and reduced emissions. Testing is taking place on smaller scale models currently, but large-scale research is likely already underway at larger defense companies. Patents and research related to greater modularity in engine design are always being produced and bought by large companies looking to revolutionize the next generation of engines. In the future, this technology will likely be used to propel passenger and cargo aircraft up to greater speeds where ramjet engines can be effective. Outside of aircraft, power production turbines will likely also implement this technology as it would allow for smaller, more efficient power production.

VII. Conclusion

Variable geometry in gas turbine engines represents an innovation for performance standards across aviation and energy sectors. Through dynamic adaptation of engine components such as nozzles, combustors, turbines, and compressors; variable geometry engines achieve increased efficiency and environmental benefits as well maintaining operational flexibility.

Key findings of this study include:

1. **Enhanced Efficiency**: Experimental data and simulations demonstrate significant reductions in Specific Fuel Consumption (SFC) and improvements in thrust-to-weight ratios. Engines with variable geometries offer dynamic performance comparable to multiple traditional engines, increasing their versatility across diverse applications.
2. **Environmental Benefits**: Variable geometry systems facilitate precise combustion control, significantly reducing harmful emissions such as nitrogen oxides (NOx) and carbon monoxide (CO). This positions technology as a cornerstone in the pursuit of greener aviation solutions.
3. **Scalability and Feasibility**: While challenges such as material limitations and cost must be addressed, ongoing advancements in high-temperature alloys and computational modeling indicate that scalable, large-scale applications are achievable.

The implications of these advancements go beyond the aviation industry. Research regarding variable turbine geometry in steam power plants is more promising than in gas turbine engines because they operate at a lower temperature. Therefore, utilizing variable geometry without the risk of excessive heat damage or increased fatigue on those parts is possible. Power generation turbines that contain variable geometries can improve efficiency and reduce emissions, supporting global energy sustainability goals. The defense and commercial aviation would have adaptable engines that could propel next-generation aircraft with improved speed, range, and environmental performance.

However, little is known about testing intermediate or large-scale engines, the concepts and techniques implemented in small scale testing should very easily translate to full scale engines without much adaptation.

In conclusion, variable geometry engines hold the potential to not only enhance the capabilities of current aviation systems as well addressing broader global challenges in sustainability and efficiency. Investing in research and development today, the industry can unlock a future of cleaner, faster, and more efficient propulsion technologies.

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