

Aerodynamic Calculation and Computer Numerical Simulation Methods Applied in Jet Engine Research

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Abstract. The development status of aero-engines is a sign of a country's technological development level and comprehensive national strength. Jet engines undergone a rapid development since being invented and are widely applied in both commercial and military aircraft nowadays. The objective of jet engines is to provide thrust for aircraft and maintain high performance in different flight segments. Engine design choice must be compromised to balance different selection criteria. This article reviews the development history of jet engines and reviews the development paths of jet engines in various technical fields in detail. It also summarizes the current state and development of jet engines from the civil and military fields and finally looks forward to the future development of jet engines. The discussion of several publications shows that considerable attention has been paid in reducing emissions, increasing fuel efficiency and reducing noise. Advanced manufacturing technologies and materials could improve engine performance. Establish new operations could be another future direction while it has limitations. Bio-fuel could be a promising solution in reducing emissions while its feasibility in meeting real operating conditions still need to be investigated.

Keywords: Jet Engine; Aerodynamic Calculation; reducing emissions; increasing fuel efficiency.

1. Introduction

Jet engines are a type of reaction engine that generates thrust by discharging fast-moving exhaust air, which can be divided into airbreathing and non-airbreathing engines, Figure 1 is a diagram of the working principle of a jet engine. Figure 2 shows the classification of jet engines. Compared to its predecessor, piston engines, which uses an internal combustion engine to drive the propeller for thrust, jet engines produce doubles the thrust provided by piston engine of equal weight; the fuel efficiency of jet engine surpasses piston engine in high-speed range (>500 miles/hour); it also offers superior reliability and longevity due to inherently smoother structure [1].

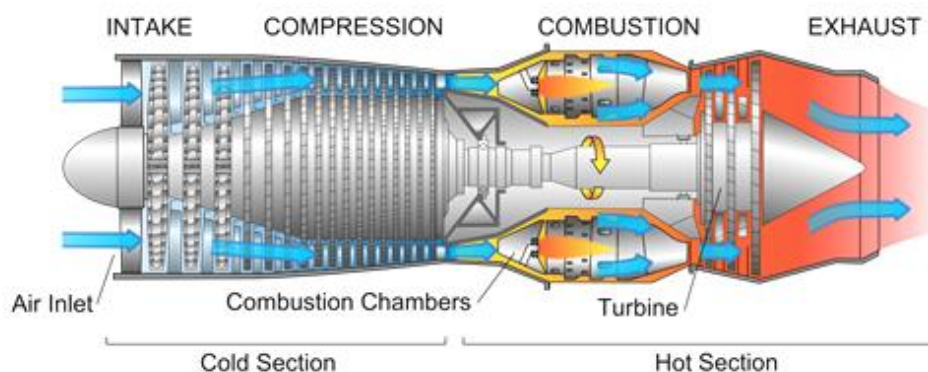


Figure 1. Working principle diagram of a jet engine

Since its invention in the 1930s, it has evolved in terms of performances and variations for different applications, making it the most widely used engine in commercial and military fields. Commercially, the increased thrust and fuel efficiency of jet engines allow newer planes to have increased passenger capacity and reduced average cost, making flying less of a luxury for the rich but more of a fast and convenient way of travel for common people. Additionally, jet engines' continually increasing reliability and noise control guarantee a safer and more enjoyable flying experience. Currently, more than 25000 large commercial jet airplanes are in operation throughout the world, with an expected annual growth of 3.4%. Militarily, jet engines with higher thrust to weight ratios and high-speed performances are favoured in exchange for higher maximum speed and increased maneuverability in the early years of development. In addition to conventional gas turbine jets, two engine types, ramjet, and scramjet are specifically designed to operate at ultra-high speed (>3 Mach) for military aircraft. For example, the top speed of SR-71 scout reconnaissance aircraft with turboramjet engine commissioned in 1966 (2193 mph) is four times faster than ME262, one of the earliest jets first flights in 1941(540 mph). Military jet engines are also divided into specific varieties to fulfil the need of different military aircraft. For example, turboshaft jet engines, which comprise a turbojet with an additional turbine and power shaft, are developed to fit the need of helicopters. In contrast, a turbojet engine exhaust duct modification allows thrust vectoring for vertical take-off and landing fighters. The more recent development of stealth technology enables a new generation of jet engines to reflect off a larger percentage of radar waves. The development of military jets creates a competitive research environment for rival countries, which leads to more new technology being put into practice. This technology will be providing benefits for common people upon commercialization [2].

This paper aims to review the current status and design choice of jet engines and evaluate the feasibilities of several proposed future developments. Backgrounds of jet engines including thrust generation principle, their classification and performance measurements will also be explained in this report.

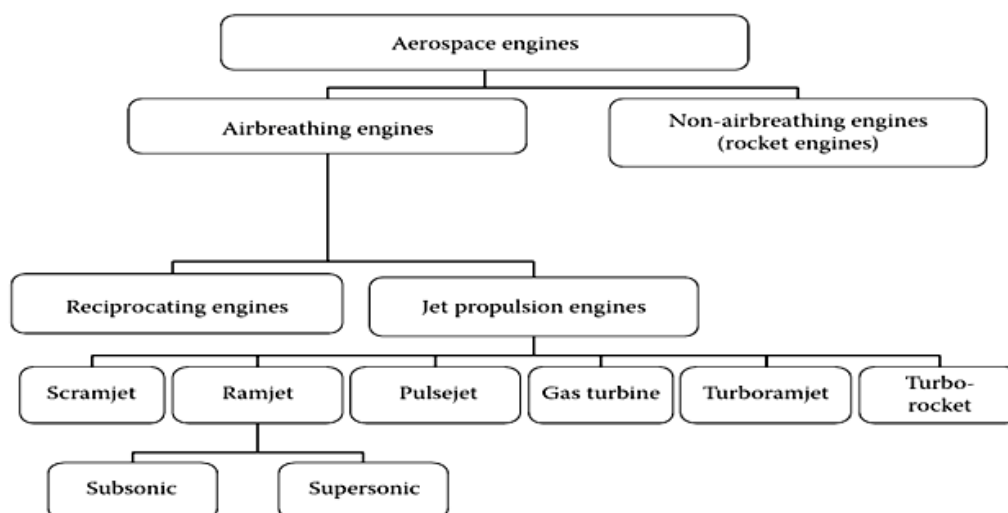


Figure 2. Classification of jet engines

2. Development Path

2.1. Thrust Generation

Aircraft is pushed forward and propelled by thrust force in flight stages, while thrust can also be used reversely as a braking force in landing. The essential of the jet engine is converting chemical energy, which is stored with liquid fuel, into mechanical energy. Thrust is produced by increasing the momentum of airflow through this conversion. The amount of thrust depends on many factors such as the mass flow rates in both inlet and outlet, fuel-to-air ratio (FAR), flight speed, and exhaust pressure [3]. By assuming the airflow in the control volume is steady, and the external flow is

reversible, the expression of thrust force can be derived by applying both Newton's laws of motion and the integral forms of conservation laws of mass and momentum, which can be shown as

$$\text{Net thrust} = \text{Gross thrust} - \text{Momentum drag} \quad (1)$$

2.2. Jet Engine Classification

Jet engines can be subdivided into ramjet, pulsejet, scramjet, gas turbines, turboram and turborocket engines.

2.2.1 Ramjet.

The ramjet engine contains an air inlet, a combustion zone and a convergent or convergent-divergent nozzle. The kinetic energy of air decreases while its pressure energy increases when air is being forced into the divergent inlet [4]. The air is then mixed with fuel and burned in the combustion chamber. The hot exhaust gases will generate thrust to aircraft in the nozzle. Ramjet is advantaged in the simple design while it has low efficiency at subsonic flight speeds and high-temperature operation conditions [5].

2.2.2 Pulsejet.

Compared to the ramjet engine, pulsejet also has a simple layout, while its combustion chamber has a series of spring-loaded one-way valves. Therefore, the combustion process in pulsejet is intermittent rather than continuous in a ramjet. The valve will be closed after the air intake to prevent backflow. Then, the valves will open again to absorb the fresh air and restart the process since hot gas has discharged and the pressure has decreased [6]. Although the pulsejet engine can deliver thrust from rest, it has low efficiency, low flight speed and high noise [1].

2.2.3 Scramjet.

Scramjet is a kind of ramjet applied in supersonic flight. Its maximum speed could reach 12 Mach at the endo-atmosphere. The difference between scramjet and ramjet is that scramjet decreases the incoming airspeed to subsonic while the combustion process occurs at supersonic velocity [7]. Scramjet generally uses hydrogen as fuel and is aerodynamically complicated.

2.2.4 Gas turbines.

Gas turbines are a type of aero-engines and can be further divided into turbojet, turboprop, turbofan and turboshaft engines. Turbojet engines, firstly developed in the 1940s, were milestones of aircraft engines since they significantly reduced flight and maintenance costs and improved the safety of the commercial aviation industry [8]. Compared to piston engines, turbojet engines are more efficient at high flight speeds (even supersonic). They provide markedly greater thrust-to-weight ratio and, thus, larger aircraft ranges and payloads. Turboprop engines are generally applied in transport aircraft since they have relatively high efficiency at both high and low speeds [1]. The thrust in turboprop engines is generated from rotating shaft power rather than from exhaust gas in turbojet engines. Their shafts connect large propellers to the gas turbine, the rotating speed can be controlled by a gearbox [5].

Turbofan engines, the most recently developed jet engine, have advantages from both turboprop and turbojet engines. They have better performance and lower cost than turbojet engines at low speed and altitude. In the front fan of the gas turbine near the tip, the speed could reach supersonic, and near the hub, there is general subsonic flow [9]. The major difference between them and other gas turbine engines is the bypass air design, where air mostly compressed by the fan bypasses the combustor and turbines. There are two streams of air passing through the engine. The primary stream flow through the engine core, and the secondary stream travel through the large internal ducted fan [5]. This bypass air stream will finally be ducted through the cold nozzle or mixed with hot gas exhaust to cool down the temperature in the combustion chamber. This bypass design defines bypass ratio (bpr), which is the ratio of the mass of cooler air bypassed through the cold duct to the mass of hotter air passing through the engine core. Turbofan engines with bpr vary from 0.2 to 1 are called low bypass engines, the medium bypass engines have bpr between 1 to 4, and the high bypass engines have bpr greater

than 5 [3]. The bypass design can efficiently use the high-temperature ratios and high-pressure ratios in the engine core to cool the combustion chamber, steady the mixture of fuel-air gases and decrease the engine noise [4].

Turboshaft engines are used in helicopters. They differ from turboprop in that residual thrust generated by the shaft in driving the propeller is avoided in turboshaft engines since they have further expansion turbine systems [1].

2.2.5 Turboramjet.

Turboramjet engines combine the turbojet engine for high flight speed and ramjet engine for high performance. They have variable intake and nozzle at the front and rear, respectively and are applied where high speed is required in a cruise condition. Turboramjet performs similarly to turbojet during the aircraft take-off stage. At the same time, it will function in ramjet mode in other stages since the incoming air is ducted into post-burning jet pipe [10].

2.2.6 Turborocket.

Turborocket engines are similar to turboramjet, while the oxidizer used in the rocket-type combustion chamber comes from their carrying liquid oxygen rather than intake air. They also use additional fuel-rich gas before the expansion process to cool the chamber where the temperature could reach 3500 degrees [3]. Compared to turboramjet engines, they have a lower weight and smaller sizes. However, the low fuel economy made it more suitable for short-duration aircraft in the space-launcher type where high speed and altitude performance is critical [11].

2.3. Performance and Efficiency

Engines' ability to efficiently provide thrust for aircraft during different stages determines their performance. Jet engines could be divided into single shaft engines, multi-shaft engines (with separate low-pressure and high-pressure spools), and bypass engines, the description of the performance of the different types of engines could be different [1]. For example, the behaviour of multi-shaft engines can be determined by particular flow features of turbine and nozzle. In contrast, its behaviour relates to the bypass ratio to core jet velocity for bypass engines for minimum specific fuel consumption (SFC). Several methods can be used to quantitatively measure the engine performance, such as propulsive efficiency, thermal efficiency and overall efficiency. Propulsive efficiency (η_p) is defined as the ratio of thrust power to the power imparted to the engine. It indicates the ability of the engine to convert the air kinetic energy into propulsive power and illustrates how much energy is wasted in the propelling process. For the bypass engines, the bypass ratio can be used to characterise engines, while the better descriptor of their performance is the propulsive efficiency [4].

Engine performance can also be measured by thermal efficiency (η_{th}). The difference between η_p and η_{th} is that the former is an external efficiency. At the same time, the latter is an internal efficiency since η_{th} indicates the energy conversion within the core power plant itself. η_{th} varies with pressure ratio and temperature ratio, and its definition depends on the engine type. For ramjet, scramjet, turbojet, and turbofan engines, η_{th} is the ratio of power imparted to engine airflow to the rate of engine supplied in the fuel. While for turboprop and turboshaft engines, η_{th} is expressed as the shaft power divided by the mass flow rate of fuel times the heat of reaction of the fuel used. Lastly, the overall efficiency is the product of propulsive efficiency and thermal efficiency [5].

Continuous development in jet engines is highly demanded to meet the requirements based on safety, economic and environmental factors. Researchers are studying how to improve fuel efficiency and engine reliability, reducing greenhouse gas and particle emissions and decreasing noise. Trivedi et al. claimed that the greenhouse gas emissions could be reduced by 60–80% when mixing micro-algae biofuels with conventional jet fuel [7, 8].

Another more radical solution is developing more electric aircraft (MEA) or even all electric aircraft (AEA), they have the potential in improving jet engine characters. In contrast, at the cost of substantial changes in infrastructure and aircraft capabilities, which also leads to huge investigation budget and high innovation risk [6]. Developing hybridized power source which combines batteries,

fuel cells, jet engines is a proposed solution. This hybrid propulsion and power system balance the disadvantages of these three power sources and provides higher thrust and lower SFC in take-off and cruise stages compared to a pure jet engine power system [9]. This is because fuel cells have a natural advantage in lower fuel consumption and fewer emissions. Several more promising schemes were suggested and will be further evaluated in the latter section.

3. Current Status of Jet Engines

3.1. Civil Transport

Figure 3 is a schematic diagram of a civil jet engine model. Jet engines are required to provide high performance under different operating conditions, such as high ambient temperature, heavy rain, strong wind and snow. The engine selection criteria base on aircraft size, flight range, speed, aerodynamics behaviour and operation way [11]. However, each factor could pull the engine design in a different direction. For example, the engine design consideration for the aerodynamic aspect conflicts with the mechanical aspect. Thus, the design choice must be compromised and will typically involve numerical simulations to calculate the optimized combination of high temperature and pressure ratios in the engine core [2].

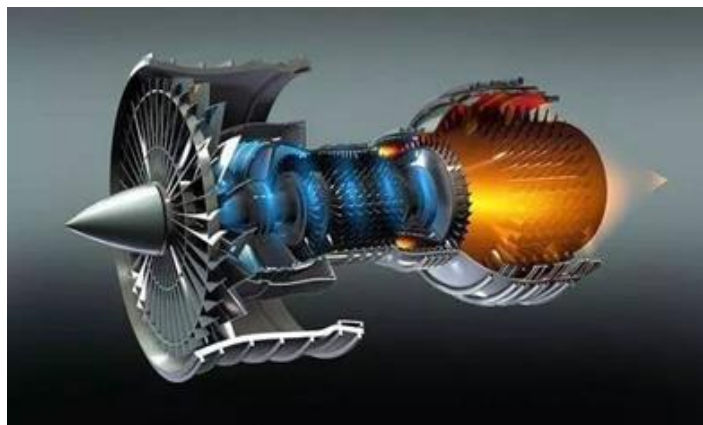


Figure 3. Sketch of the model of a civil jet engine

The design point, the flight point where the temperature and pressure ratio, fan pressure ratio and rotational speed occur simultaneously with the highest allowed turbine inlet temperature (T_{04}), determines the crucial decision of engine selection. In the early stage of aviation, design points commonly focused on the thrust in the take-off stage. However, nowadays, it varies for different types of engines and could occur in take-off, top of climb or cruise stage [5]. Therefore, the designer must recognize the varying requirements for different aircraft types in short or long range for both civil and military applications. Therefore, the following part of this section will focus on the current status of jet engine design for both civil transport and military aircraft.

Currently, the commonly used civil transport are Boeing 747-8, 777-200 LR, 777-300 ER, 787-8 and 787-9 Dreamliner; Airbus A340-500, A340-600, A380, A350-900 and A350-1000 [1]. The nature of commercial aircraft is moving passengers safely with the least environmental impact (minimum greenhouse gas and harmful gas emissions). Minimum noise during both cruise, take-off, and landing stages is important to satisfy passengers' experience and local airport regulations [4].

Compared to military aircraft, the range of critical operating conditions for civil transport is relatively small. Civil jet engines provide lower specific thrust since the aircraft turn during flight is gentler. They are also larger in size and heavier in weight since their sizes are fixed by the thrust requirement at the top of the climb. In addition, the turbofan engines will have a higher bypass ratio with a lower fan pressure ratio than that in military applications [3]. In the aspect of cost and efficiency, the civil engine requires lower fuel burn and thus, provides lower fuel consumption and higher efficiency.

The maximum cruising Mach number for civil aircraft is generally less than one (about 0.5 at sea level), and their lift is equal to drag which is about twenty at cruise. Therefore, the efficiency and fuel economy largely depend on the specific fuel consumption (SFC) and lift-to-drag ratio ($L=D$) under cruise condition. Therefore, SFC and range are two of the critical engine design issues, SFC through more than ten flight hours is typically the dominant parameter for civil engine design. For example, the long-range, wide-body twin-engine aircraft B787 and A350 are widely used for their high efficiency resulting from the higher $L=D$ and lower SFC than small single-aisle aircraft for short-range flight [1]. Additionally, the Airbus A330Neo with a new engine option was announced in 2014 and delivered in 2017. It claimed provided a more efficient engine with a larger fan, which could offer fuel-burn savings up to 10% [6]. This improved fuel efficiency leads to a similar performance with B737 while with a significant cost saving.

Safety is another crucial design consideration. Jet engines must be as most reliable as possible for commercial aircraft. They need to provide acceptable safety during the long-range flight even when one of the engines is failed. This safety performance can be defined as extended-range twin-engine operations performance standards (ETOPS). Take the twin-engine aircraft as an example. B787 and A350 have 330 minutes and 350 minutes ETOPS, respectively [2].

3.2. Military Aircraft

Military aircraft can be divided into different types. Examples of fifth-generation long take-off distance fighters are F-22 Raptor, Sukhoi Su-32, 34 and superjet 100, Chengdu J-20 and Shenyang J-31. F-35 series can represent short take-off military aircraft, and the SR-71 Blackbird is an example of high-altitude reconnaissance aircraft [8]. In recent years, the military jet engines have developed, graded by thrust and scale, three levels: small engines, utilized on drones, cruise missiles or several kinds of air-to-air missiles; Medium engines, usually turbofan but also some turbojets, utilized on multi-purpose fighters and interceptors; Large engines, almost only turbofan and some turbo-props, which are commonly used on bombers and military transport vehicles. Their engine design criteria differ from that of civil transport since military aircraft must fly faster. They could reach a 1.2 Mach number at sea level and more than 2 Mach at higher altitudes. The typical lift is equal to drag which is about six to seven, which is lower than civil transport. Therefore, the fuel economy and SFC will be trading off under this circumstance, leading to higher fuel consumption.

Jet engines applied in military aircraft are generally low bypass ratio turbofans, and their engine layouts are more complicated and varied than those for civil aircraft [9]. This is because the take-off thrust, rate of climb, and maneuverability are the critical considerations for fighters since the accomplishment of the mission is the most urgent requirement [10]. Jet engines performance under several operating conditions for high-speed combat fighters is important. In other words, aircraft need to accomplish sharp turns at high speed and rapid acceleration and to be more agile.

Turning in high altitude requires high lift generated by wings, ailerons and other structures. Weight reduction also plays a significant role in engine design because engine weight is highly related to aircraft's overall weight. Take a twin-engine aircraft as an example. Each 1 kg weight increase in the jet engine will lead to an 8-10 kg increase in subsonic aircraft weight, and even a 12-20 kg increase for supersonic aircraft [11]. The combination needs of increasing lift and reducing weight indicates a much higher thrust-to-weight ratio than civil aircraft. Thus, these special requirements demand a lower bypass ratio.

Additionally, military jet engines are relatively lower in weight and smaller in size since the maximum determines their engine size required turning rate during flight missions [5]. The material used in military engines needs to withstand higher temperatures since in temperature can rise well above the temperature experienced for sea-level take-off. Figure 4 shows the temperature distribution of a military jet engine during operation.

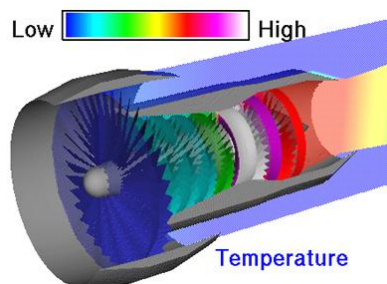


Figure 4. The temperature distribution of a military jet engine during operation

Different sorts of engines have different persuades, but they have some common aims: A longer lifespan, fewer fuel costs, better maintenance capacity and higher reliability.

3.2.1 Small scale military engine development.

Drones and cruise missiles have different requirements for jet engines in comparison with manned aircraft. For drones, the engines are required to be light, durable and have a long lifespan, low fuel cost so the drones can maintain flight in the target area for long periods. For cruise missiles, the engines are required to be cheap and have high thrust, while duration and reliability are not so important. Turbofans and turbojets are quite common on military drones, including AE-3007, the power source of Global Hawk and J69 for many smaller drones.

These engines are usually designed for specific categories. Therefore, they persuade a complicated balance between duration, cost, maintenance capacity and performance. Due to this issue, it is hard to summarize whether these engines have a common target. In general, basically, all these engines are persuading a smaller mass and lower cost.

3.2.2 Medium-scale military engine development.

These engines are the main engines developed for tactic airplanes, including famous AL-31F series, F100 series and many other well-known military engines. These engines are very different from others because they persuade a higher thrust-weight ratio, and the cost is not an important issue. This makes medium military engines special, as their producers pay billions of dollars in their development to enable better performances than ever. The main sorts of these engines are now believed to process a TWR of 10 or larger.

According to Liu [9], in 2015-2020, there might be military turbofan engines with TWR range 15-20 being developed. With far fewer parts and Titanium-based materials contributed to weight reduction, higher turbine inlet temperature, and removal of afterburner contributed to higher combustion efficiency, it is possible to improve the performances of current engines to a higher level.

3.2.3 Large scale military engine development.

Engines used on massive military aircraft (tankers and transport planes) are basically the same as those used on commercial aircraft. At the same time, only a few alternatives have to be done.

While it is worth noting that for civil or military freighter aircraft, such as Airbus A400, Airbus Beluga, Boeing C-17, Lockheed Galaxy C-5, An 225, Il 76, the maximum payload is their main engine design requirement rather than the fuel economy for civil transport or maneuverability for fighters [4].

4. Future Development of Jet Engines

4.1. Future trends

People are no longer confined to the surface of life. They began to explore the sky, higher and farther. The aviation industry is rapidly growing with an annual expansion rate of 5%. Hans von Ohain of Germany was the designer of the first operational jet engine, and a performed flight test first started in 1941, while jet engine design has followed its logical path and remained relatively

unchanged for more than 60 years [12]. The high cost of developing new engines is a strong limit prevent the frequent optimization. Two main U.S. engine manufacturers aiming to develop the latest engine technology are Boeing and Lockheed Martin, and Boeing and Airbus are the two civil aviation companies who continuously publishing new aircraft. Nowadays, their most recent aircraft are B787 Dreamliner and A380, both focus the most on the passenger experience and fuel economy [13].

This trend indicates that the fuel efficiency at the same level of thrust will be the most concern for the technological developments in future civil engines. The reason is that 40% of direct aircraft operating cost is composed of fuel expenditure, however, the fluctuation of global fuel prices due to political factors continuously obstructing airlines establish long-term market strategies [12]. Another reason for improving fuel efficiency is the rising demands for jet fuels, where is predicted to be a 38% increase by the year 2025 [14]. Therefore, aircraft must be more fuel efficiency in order to make profit. Meanwhile, civil transport contributes to about 2.6% of global CO₂ emissions, even worse, this number is predicted to reach 5% by 2050 due to the continued expansion of aviation industry [12]. Thus, environmental issues are likely to play a more important role in engine design since the possible regulations require to reduce the fuel burn, and larger public attention have brought into greenhouse gas (GHG) emissions, such as CO₂ and NO_x. Besides greenhouse gas emissions, particle emission is another problem need to be addressed since it impacts air quality in both upper atmosphere and local airport [15]. The release of fine and soot particles from jet engines can be reduced by changing in engine design while this will require fruitful research. Additionally, civil engines need to be more reliable, lower noise and less weight. These improvements can also contribute to the cost reduction in aircraft since they could prevent the penalty of noise and greenhouse gas emission from local airports. The future geometries of engine might be adopted for minimise noise rather than optimal aerodynamic performance in order to meet noise regulations during take-off and landing [16].

In terms of military aircraft, increasing specific thrust is the trend in engine design. The development and optimization are restricted by the extensive research requirements result from the huge cost of military engine. U.S. tends to run engine competitions between General Electric and Pratt and Whitney companies [17]. While the trend of engine development in Europe is designing and investigating by a single company and manufacturing by an international consortium.

4.2. Possible Solutions

In order to meet the demands of increasing fuel efficiency and reducing noise, weight and emissions, new technology, better operations and bio-fuels can be applied for jet engine design. Discovering new breakthrough technique is becoming more difficult, there is about 0.8% development in new engine technologies annually in the past 40 years. For instance, the three-shaft engine layout is the recent trend for Rolls-Royce Company, their improved material selection such as Titanium engine housing and advanced design and manufacturing technology such as 3d design and end-wall profiling, combine lead to a 70% weight saving in compressor and fan blades. Other advanced materials applied in compressor could be silicon carbide–reinforced metal matrix, which has the potential to replace the traditional compressor disks due to its high performance under ultimate stress [16]. Another example for new technology in combustor design is the advanced cooling methods, which aim to producing more stable flame during combustion [13]. This technology could extend the engine lifecycle by reducing the combustor temperature and increasing the turbine temperature, which further lead to the improvement in engine efficiency results from the increasing temperature ratio. Additionally, new developed thermal barrier coating materials can be used in the rotating part of engine to provide higher temperature tolerance and improve engine reliability [17].

The second possible direction of future jet engine design is optimizing flight operation. However, this is limited by the compressor delivery temperature and turbine inlet temperature, which means although flying more direct routes or preventing delays before take-off with engine idling has potential in efficiency improvement, this optimal operations have difficulty to achieve [18].

Using jet bio-fuels (JBF) could be a possible solution for future engine development. Unlike fossil fuels such as oil, coal and natural gas, biofuels are considered a renewable source of energy. Biofuels

are generally considered to be cost-effective and environmentally friendly alternatives to oil and other fossil fuels because they are more readily available. The first generation of biofuels is mainly produced by plant starch, sugar and oil. It can be easily fermented into ethanol. Biomass residues with lower use value of second-generation biofuels these residues may come from forestry, agriculture, municipal solid waste or special energy crops. The two most common biofuels currently used are ethanol and biodiesel, both of which are first-generation biofuel technologies. A flight path set by the European Energy Commission claimed is able to reduce 3% GHG emission was by using two million tonnes of biofuel [19]. Another example is a flight applied a biofuel with hydro-processed ester by Singapore Airline's Airbus A350-900 from San Francisco to Singapore in 2017, the carbon emissions was reduced by using waste cooking and jet fuel [20].

However, feasibility of JBF in real application and production still requires further studies. For example, Islam et al. reported that comparing to conventional petroleum-derived jet fuel, algae and *Spirulina* biodiesel may reduce the emission in CO, CO₂ and NO_x by up to 50% [19], and they could also protect airlines operation against sudden changes in jet fuel prices [20]. However, the positive impact on both improving engine thrust and reviving environment only occurs when low proportion of algae biofuel is mixed with jet fuel rather than high percentage [14]. Another alternative choice of jet fuel is alcohol-to-jet type fuel, researchers claim it can reduce both the particle and the greenhouse gas emissions under several operating conditions due to the absence of aromatics in alcohol [15]. While the future challenge for this type of fuel is the identification of feasible blending percentage of alcohol and jet fuel in order to meet the real soot emission regulations.

In terms of military jet engines. efficiency of engine research and development could be improved by variable cycle engine (VCE), which is a kind of aircraft jet engine designed to operate efficiently under subsonic, transonic and supersonic mixed flight conditions [7]. And this leads to the attractiveness of the variable cycle engine.

5. Conclusion

The twenty-first century is characterized by a revolutionary development in both aircraft and engine industry. In terms of civil transport, safety, fuel economic and environmentally friendly are the objectives of airlines. On the military side, achieving air superiority is the main target for most countries. Therefore, continuous development in jet engines is highly demand. This report highlighted the current design choices by comparing the differences between civil and military engines and illustrated some future directions in jet engines developments. The feasibilities of applying new technologies, advanced materials, optimized operations and bio-fuels were analysed. The following conclusions can be drawn based on a review of publications:

1) The current design of commercial jet engines is based on safety, economic and environmental factors. Comparing to military engines, they generally have lower specific thrust, larger size and weight. The civil turbofan engines have higher bypass ratio with lower fan pressure ratio. Their higher efficiency results form larger lift-to-drag ratio and lower specific fuel consumption. In military engines, the SF C will be trade off to provide higher thrust-to-weight ratio.

2) The high investment cost and risk lead to the relative unchanging in engine optimization. However, several problems still need to be addressed in future. Firstly, improving fuel efficiency without thrust penalty could be the most concern for airlines in order to make profits. This is a combined results of the large proportion of fuel expenditure in total cost, the fluctuation of global fuel prices, and the rising demands for jet fuels. Meanwhile, reducing both the greenhouse gas and particle emissions is predicted to play a more important role in future engine design to meet environmental regulations from governments and airports. Lastly, civil engines need to be more reliable with lower noise and less weight, and military engines demand an improvement in specific thrust.

3) New technology in jet engines such as advanced cooling methods could extend their lifecycle and improve efficiency. Advanced design and manufacturing technology such as 3d design and end-

wall profiling can contribute to weight reduction in compressors. Materials such as silicon carbide–reinforced metal matrix and advanced thermal barrier coating can be used in blades and rotating parts to improve engine reliability. Optimizing flight operation has potential in efficiency improvement, while it may have difficulty to achieve since engine performance is limited by the engine temperature in compressor and turbine. Jet bio-fuel could be a solution in reducing emissions. However, further studies in the blending percentage are still required and it is generally agreed that the development of bio-fuels is an ongoing challenge and much effort is worth devoting.

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