Proceedings of the 3rd International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/25/20240927

Challenges to aviation in the global warming context

Qiwei Fan

Engineering department, University College London, London, WC1E 6BT, United Kingdom

zcemqfa@ucl.ac.uk

Abstract. The aviation sector has undergone substantial growth, leading to a corresponding increase in emissions attributed to this industry. This escalation in emissions has notably contributed to the intensification of global warming. This research provides a comprehensive examination of various prospective solutions to mitigate these emissions. Among the proposed solutions is the adoption of an intercooled turbofan engine. This specific engine type holds the promise of realizing a 3.1% reduction in fuel consumption compared to traditional engines. Furthermore, the incorporation of a recuperator in an intercooled turbofan engine could potentially lead to a significant decrease in fuel consumption by up to 30%, alongside a remarkable 20% improvement in engine efficiency. The discourse also extends to the subject of hydrogen-powered aviation, underscoring its substantial potential in achieving emissions reduction goals. However, the associated challenges, especially those related to hydrogen storage, are also explored in this study. The forthcoming era of jet engine technology may witness the amalgamation of intercooled turbofan engines and hydrogen energy sources as a viable pathway for substantial emissions reduction.

Keywords: Global warming, Emissions reduction, Intercooled turbofan engine, Hydrogen energy

1. Introduction

The aviation industry has grown rapidly in the last decades in terms of fly kilometers, which from 109 billion kilometers per year in 1960 to 8269 billion kilometers per year in 2018 [1], which leads to an increment of a 6.8 factor in CO_2 emissions [2]. This highlights the increasing influence of the aviation industry on the issue of climate change. Nowadays, global warming has become a serious issue caused by greenhouse gas emissions, and CO_2 plays a significant role, which occupies 74.4% of total greenhouse gas emissions [3]. M Klöwer et al.'s study discussed the growth in CO_2 emissions from aviation from 1980 to the beginning of COVID-19 and also predicts that the growth would be greater after 2024 [4]. Moreover, A Maccintosh and L Wallace's study indicates that reducing the increase of CO_2 emissions and effectively limiting their growth is a significant challenge, requiring further steps to address aviation-related emissions [5]. In addition, the UN emissions gap report from 2019 [6] states that in order to keep global warming to 1.5°C, emissions must be cut by 7.6% annually from 2020 to 2030. Otherwise, there would likely be a 3.2°C increase in temperature over pre-industrial levels, which will have a negative impact on agriculture, the environment, and human health.

Considering the importance of solving the problem mentioned above, some approaches are studied and discussed by researchers. F Greer et al. discussed the airport gates that provides power to airplane [7]. Airplanes are parked near airport gates to take the boarding procedure before take-off and require power from the gate, which is generated by fossil-fuel combustion equipment. Their study finds that greenhouse gas emissions, including CO_2, could be reduced by up to 97% per gate operation and even greater reduction with low-carbon electricity. Furthermore, new policies and potential strategies could also reduce CO_2 emissions. Further, in Pukhova et al.'s study, it is found that restricting the flight ranges that are no shorter than a certain threshold distance could potentially decrease the CO_2 emissions from the whole transportation sector by 7.5% [8]. Moreover, D Zachary et al.'s study shows that manipulating the flight schedule, trajectories, take-off and landing procedures could have a positive impact on the emissions [9].

The above research highlights several promising approaches to mitigate the environmental impact of the aviation sector, particularly in terms of reducing greenhouse gas emissions. However, a more comprehensive analysis of the technical problems of the aircraft needs to be analyzed for achieving low-emission aviation. This report aims to investigate methods for enhancing jet engine efficiency as an approach to reducing emissions. Additionally, environmentally sustainable energy sources that show the potential to replace fossil fuels will be discussed.

2. High-efficiency turbofan engine

2.1. Turbofan engine

Turbofan engines are commonly installed in commercial aircraft owing to their notable efficacy in subsonic conditions and commendable fuel efficiency. The turbofan engine comprises multiple components, as shown in Figure 1 [10]. The operational principles of turbofan engines involve the intake of air through a fan, which then divides into two separate pathways before entering the engine. A portion of the air is directed into the internal region of the engine, known as the engine core, where the process of combustion occurs. The remaining portion, referred to as bypass air, is channeled outside of the engine core through a duct. Following the suction process, the air is directed into a low-pressure compressor where its pressure is elevated in accordance with specific requirements. Subsequently, the air then travels to a high-pressure compressor, where it undergoes further compression to reach significantly elevated pressure levels, accompanied by a corresponding increase in temperature. The elevated pressure generated by the compressor induces a significant rise in air temperature that leads to the spontaneous initiation of the combustion process when contact with the fuel in the combustion chamber. Following the combustion process of the air-fuel mixture, the resulting combusted gas proceeds to enter both the low-pressure and high-pressure turbine, where the high-temperature gases undergo expansion and then strike the turbine blades. The power extracted by the turbine blades from the combusted mixture is sufficient to propel the low-pressure compressor and fan. The combusted mixture's remaining power is directed towards the exhaust nozzle. Once entering the nozzle, the exhaust gases undergo a conversion process whereby their pressure energy is transformed into kinetic energy, resulting in the generation of high-speed gas that pushes the airplane [11]. A typical turbofan engine structure is shown in Figure 1.

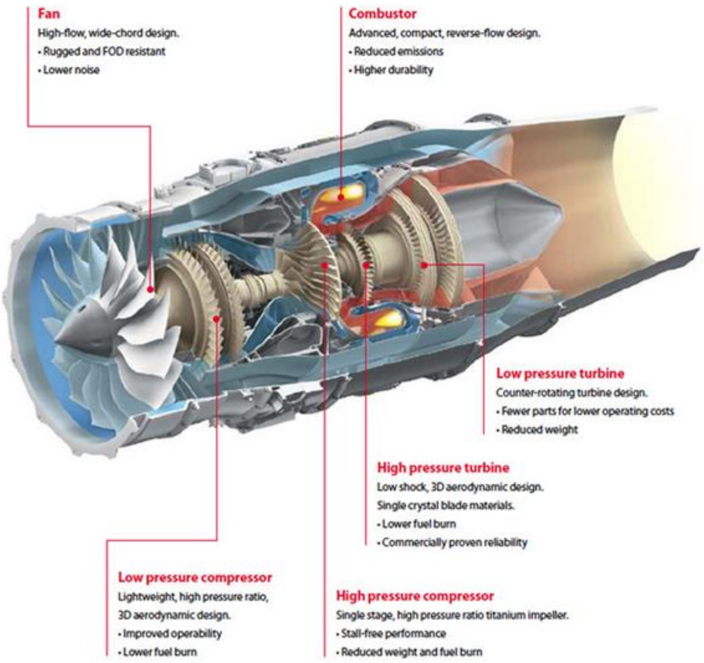

Figure 1. The structure of a turbofan engine [10]

2.2. Engine performance

Common rail fuel injection technology is an engineering method that employs high-pressure liquid fuel to facilitate engine combustion. This technology relies on a common rail, also referred to as a fuel supply rail, to deliver fuel. It elevates fuel pressure significantly using a high-pressure pump and subsequently administers fuel into the engine’s combustion chamber in accordance with predetermined parameters, including timing, pressure, and injection pattern, through an injector. The fundamental operating principle involves raising fuel pressure within the common rail pipe through the high-pressure pump. This process is monitored by a high-pressure sensor, while the Electronic Control Unit (ECU) regulates the electromagnetic flow of the common rail pump and the aperture of the regulating valve to manage the injection sequence and quantity. Ultimately, the fuel is introduced into the combustion chamber via the injector.

The purpose of jet engines is to provide thrust to push the plane. The thrust (F) can be expressed by the speed difference between the exhaust jet (V_e) and the aircraft flight velocity (V_a) multiplied by the mass flow rate ($\dot{m}$) which can be described as

$$F = \dot{m} (V\_e - V\_a)\ (1)$$

The term describes the efficiency of the thrust produced per fuel consumption can be expressed as

$$SFC = \frac{\dot{m}_f}{F} (2)$$

where $\dot{m}_f$ is the fuel consumption rate.

The total engine efficiency is the ratio between power that pushes the airplane and the thermal power from the consumed fuel, which can be described as flowing equation.

$$\eta = \frac{F \times V_a}{\dot{m}_f \times Q_f} (3)$$

where V_a is the flight speed and Q_f is the heating value of the fuel.

The total engine efficiency can be further separated to thermal efficiency (η_{th}) and propulsive efficiency (η_p). The thermal efficiency can be explained as the ratio between the kinetic energy of the exhaust air and the thermal energy from the fuel consumption, which can be defined by,

$$\eta_{th}\frac{\dot{m}_e\frac{V_e^2}{2}-\dot{m}_a\frac{V_a^2}{2}}{\dot{m}_f\times Q_f}(4)$$

How effectively exhaust air kinetics produce thrust is defined as propulsive efficiency.

$$\eta_p=\frac{F\times V_a}{\dot{m}_e\frac{V_e^2}{2}-\dot{m}_a\frac{V_a^2}{2}}(5)$$

The propulsive efficiency and thermal efficiency are interdependent, changes in one can influence the other. By adjusting the engine's features and thermal cycle parameters, it is possible to optimize both the total efficiency and fuel consumption.

2.3. Intercooled turbofan engine

In addition, water-emulsified diesel can reduce particulate matter emissions due to the inhibition of particulate matter generation and emission by water.

The intercooler is a component that is installed with engines in order to reduce the temperature of the compressed air. The air undergoes an increase in temperature through the compressor. As a result, the release of hot air transfers some thermal energy to the incoming air via the compressor's heat conduction, so elevating the temperature of the incoming air and subsequently leading to a reduction in inlet air density. The decrease in the incoming air density causes a decline in the efficiency of air intake and a reduction in oxygen density, ultimately leading to a loss in power output. The installation of intercoolers has the potential to enhance both the air intake efficiency and the overall engine efficiency [12]. Furthermore, a reduction in NOx emissions can be achieved by lowering the air temperature within the combustor [13].

As introduced the turbofan engine and also the intercooler, by combining them, the engine could reach a higher efficiency. In order to construct an intercooled turbofan engine with great performance, it is essential to address a variety of concerns and determine certain criteria. The main parameters required are fan pressure ratio (FPR), overall pressure ratio (OPR), bypass ratio (BPR) and the pressure ratio split between the intermediate-pressure compressor (IPC) and high-pressure compressor (HPC). In L xu and T Grönstedt's study, they designed and analyzed an intercooled turbofan engine, as shown in Figure 2 [14]. The intercooler is situated inside the top part of the engine, specifically within the bypass channel. The intercooler's diffuser divides the bypass flow into two separate streams respectively, an internal bypass flow and an exterior bypass flow. Maintaining equal static pressure on both the upstream and downstream sides of the diffuser trailing edge is required. Consequently, when the pressure on the internal side decreases, the corresponding mass flow rate will fall. The pressure reduction on the exterior side would also result in a decrease in the mass flow rate of the internal flow. Thus, by modifying the design parameters to minimize pressure reducing on the external side and ensuring sufficient airflow through the internal channel for effective heat exchange.

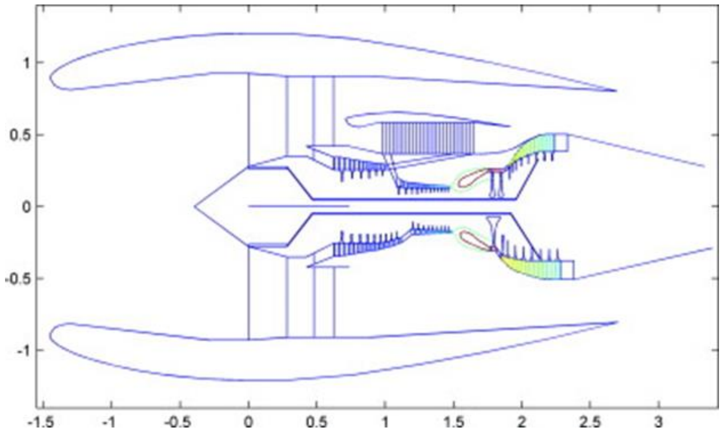

Figure 2. The structure of the intercooled engine [14]

The researchers established a comparative analysis between an intercooled engine and an optimum engine in order to evaluate the performance of the intercooled engine. Table 1 presents the efficiency of the components and the restrictions for optimization.

Table 1. Engine design parameters [14]

Parameter	Value
Fan efficiency (%)	91.0
Intermediate-pressure compressor efficiency (%)	91.0
High-pressure compressor efficiency (%)	91.5
High-pressure turbine efficiency (%)	90.0
Low-pressure turbine efficiency (%)	91.5
Combustor inlet temperature (K)	900
Combustor outlet temperature (K)	1850

The traditional turbofan engine was subjected to testing via an examination of the fan pressure ratio (FPR), overall pressure ratio (OPR), and bypass ratio (BPR). The testing includes several stages of a flight, including take-off (TO), mid-cruise (MC) and top-of-climb (TOC). The total distance covered during the test flight amounts to 925 kilometers. The data shown in Table 2 displays the optimal cycle parameters, and the study determined that the minimal fuel consumption for the flight was 3633 kilograms.

Table 2. Traditional engine parameters [14]

Parameter	TO	TOC	MC
OPR	37.25	47.01	43.32
FPR	1.463	1.575	1.529
BPR	11.83	11.50	11.97
Combustor inlet temperature (K)	900.0	798.3	779.0
Combustor outlet temperature (K)	1850.0	1641.1	1580.4
SFC (mg/Ns)	7.444	14.72	14.58

The optimization factors of the traditional engine are FPR, BPR, and OPR. However, the performance of the turbofan engine with intercoolers is influenced to a greater extent by other factors, including the pressure ratio in the high-pressure compressor (HPC) and intermediate-pressure compressor (IPC). Moreover, the design characteristics of the intercooler may be modified in order to decrease the fuel consumption of the engine. The characteristics of the intercooler that have been determined are presented in a concise manner in Table 3.

Table 3. Intercooled turbofan engine parameters [14]

Parameter	TO	TOC	MC
OPR	57.15	71.99	66.48
FPR	1.478	1.591	1.544
BPR	12.17	11.69	12.15
IPC pressure ratio	3.301	3.478	3.389
HPC pressure ratio	11.71	13.71	12.70
Combustor inlet temperature (K)	900.0	796.2	776.5
Combustor outlet temperature (K)	1850.0	1631.5	1573.0
SFC (mg/Ns)	7.191	14.23	14.11

Results indicate that, with little variation in other variables, adjusting the pressure ratio of the HPC and IPC results in a reduced specific fuel consumption (SFC). Consequently, the intercooled engine exhibited a fuel consumption of 3522 kg during the flight, representing a 3.1% decrease compared to the conventional engine.

2.4. *Intercooled turbofan engine*

The recuperator is a heat exchanger that features distinct flow routes for each fluid, which are contained within separate tubes. Heat transfer occurs through the surfaces that separate these passages. Recuperators, such as economizers, are commonly employed in the field of power engineering with the aim of enhancing the overall efficiency of thermodynamic cycles. As an illustration, within the context of a gas turbine engine. The recuperator facilitates the transfer of a portion of the waste heat present in the exhaust to the compressed air, effectively preheating the air before its entry into the combustion chamber. Numerous recuperators are engineered in the form of counter-flow heat exchangers. Moreover, in aviation engines, the recuperator can be used in turbofan engines. Figure 3 shows a proposed recuperative engine [15]. After leaving the turbine output, the exhaust gas is sent via a number of heat exchangers placed inside the exhaust nozzle. The high-temperature exhaust gas and the compressor air's relatively lower temperature engage in a heat transfer process. As a result of the latter being diverted into the combustion chamber, the combustion process is boosted, reducing pollutants and increasing fuel efficiency. Both of these technologies have the potential to produce fuel savings of up to 20% and CO_2 and NO_x emission reductions of up to 20% and 80%, respectively.

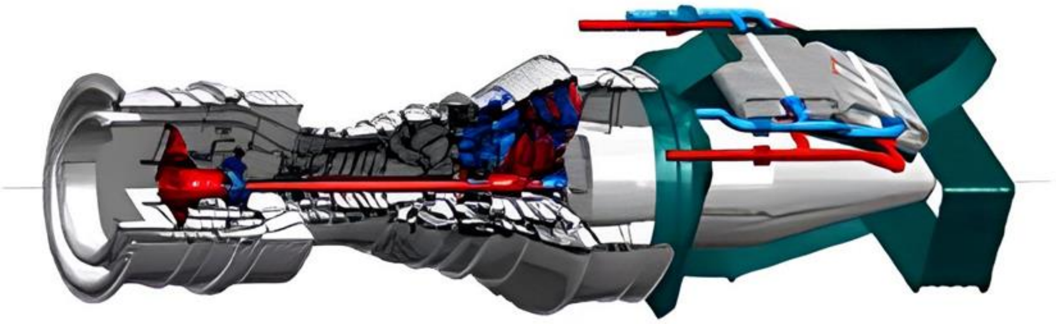

Figure 3. The turbofan engine with a recuperator [15]

In H Omar et al.'s study, they analyzed the performance of a recuperative turbofan engine with an intercooler by optimizing the thermodynamic parameters [16]. The optimized parameters are turbine inlet temperature (T_4), compressor pressure ratio (r_c), bypass ratio (m), fan pressure ratio (r_{fan}), the efficiencies of the intercooler (η_{inter}) and recuperator (η_{recu}). The evaluation of engine performance encompasses various perspectives, including the combined weight of the power plant and fuel ($M_{engine+fuel}$) and fuel consumption per ton-kilometer (C_{sp}). The chosen aircraft, acting as the prototype, bears a strong resemblance to the distinguishing characteristics of the commercial Boeing 737 MAX 7. For the intercooler and recuperator, the researchers determined a range of effectiveness values that varied between 0 and 0.9. In cruising mode, the gas temperature at the turbine was assumed to be 1400, 1600, 1800, and 2000 K. By taking into account the aerodynamic characteristics of the aircraft and simulating different flight cycles, the necessary power plant thrust was determined, which served as the basis for determining the engine thrust of the aircraft. Figures 4 and 5 show the outcomes of optimizing thermodynamic parameters for a turbofan engine that includes an intercooler and a recuperator. The results of analyzing each of the six factors that were optimized are shown in these figures. Depending on the turbine inlet temperature, the engine's regionally optimal characteristics are shown in the black zone at 1400K turbine intake temperature, 1600K in the orange zone, 1800K in the green zone, and 2000K in the red zone. The findings indicate that the intercooler and recuperator heat exchanger effectiveness increases, as do the ideal bypass ratio and compressor pressure ratio.

Additionally, as the temperature of the turbine inlet rises, the weight of the fuel and power plant decreases, as does the fuel consumption, which boosts the efficiency of the turbofan engine up to 30%.

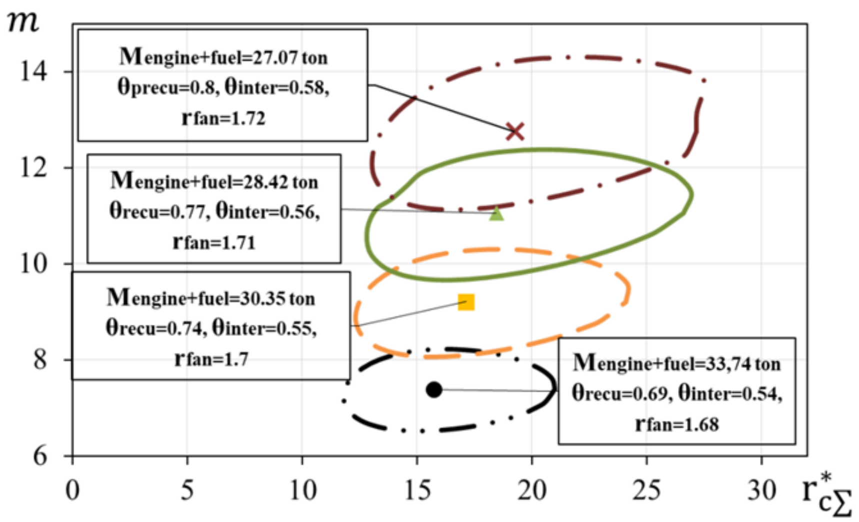

Figure 4. The optimal parameters of the engine according to the criteria weight of the fuel and power plant [16]

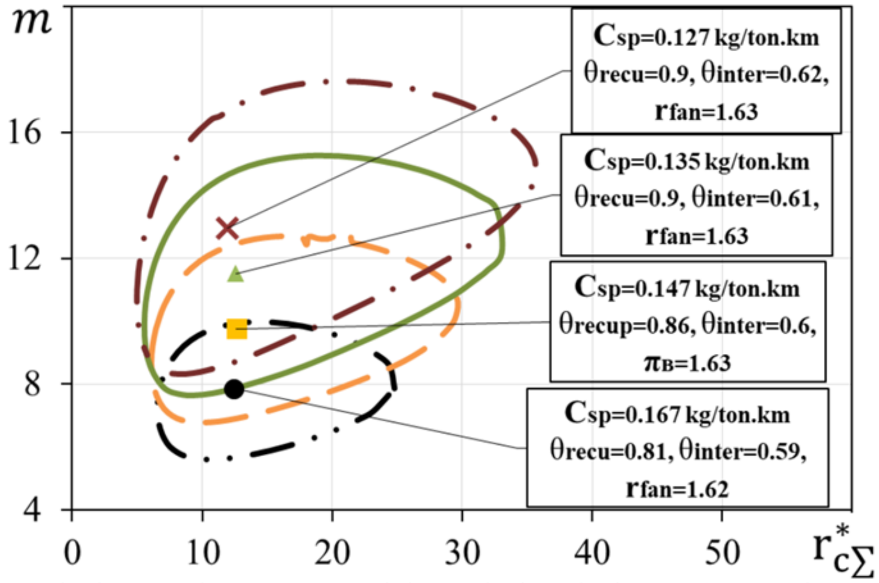

Figure 5. The optimal parameters of the engine according to the criteria fuel consumption [16]

Additionally, Figures 6 and 7 illustrate how the recuperator and intercooler's heat exchanger effectiveness affects the ideal compressor pressure ratio and bypass ratio for a recuperative turbofan engine with an intercooler. These ideal values are established by taking into account the weight of the power plant and fuel consumption. The black zone represents the region where the intercooler efficiency (η_{inter}) and recuperator efficiency (η_{recu}) are both 0.0. The orange zone represents the scenario where the intercooler efficiency (η_{inter}) is 0.9 and the recuperator efficiency (η_{recu}) is 0.5. The green zone represents the situation where the intercooler efficiency (η_{inter}) is 0.9 and the recuperator efficiency

(η_{recu}) is 0.7. Lastly, the red zone represents the case where both the intercooler efficiency (η_{inter}) and recuperator efficiency (η_{recu}) are 0.9.

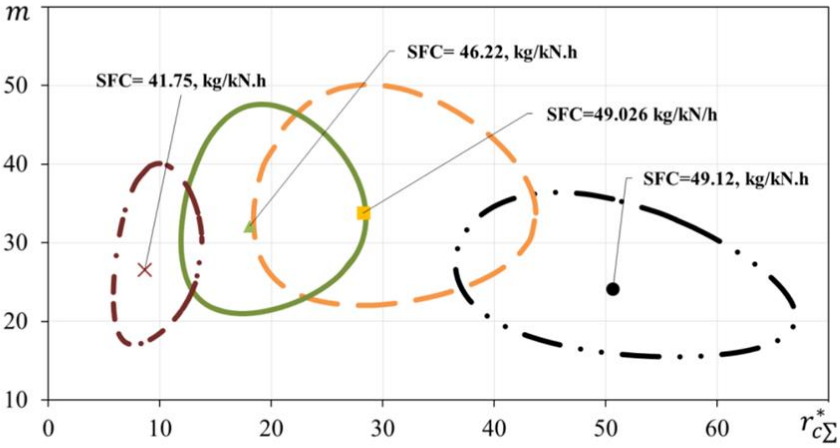

Figure 6. The optimal parameters of the engine according to the criteria specific fuel consumption (SFC) [16]

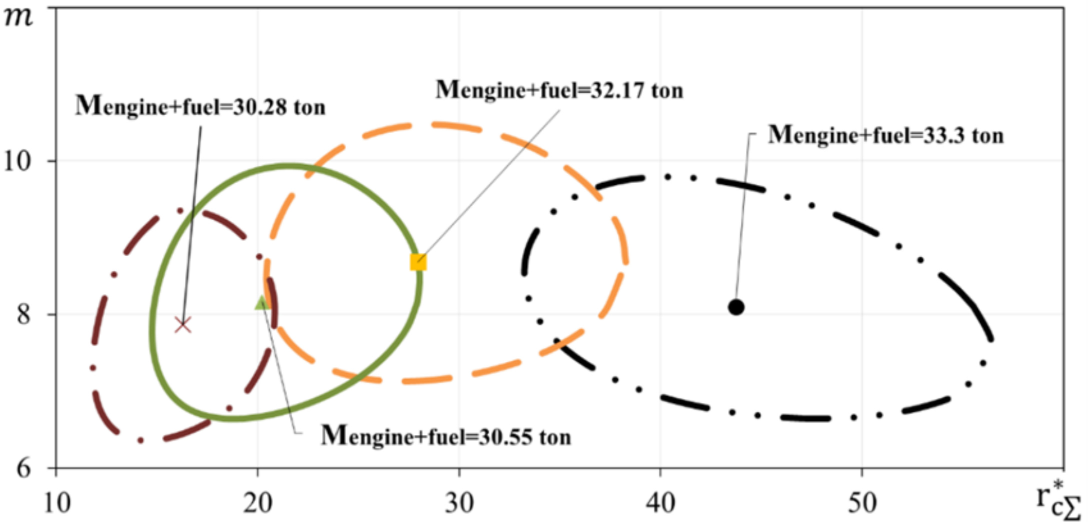

Figure 7. The optimal parameters of the engine according to the criteria weight of the fuel and power plant [16]

The findings indicate that the ideal compressor pressure ratio values drop dramatically, sometimes by up to five times, as the intercooler and recuperator's heat exchanger effectiveness rises. Furthermore, as the recuperator and intercooler's heat exchanger effectiveness increases, the ideal bypass ratio value drops by about 25 to 30%. Additionally, it may result in a 15% decrease in fuel consumption as well as a 10% decrease in the engine and fuel's combined weight. This could therefore lead to a 15–20% increase in efficiency for a turbofan engine.

3. Hydrogen-energy-powered Aviation

The current internal combustion engines used in airplanes have the potential to undergo modifications that enable them to operate on alternative fuels, hence leading to enhanced environmental performance. Currently, hydrogen combustion, whether in the form of gas or liquid, is becoming recognized as a highly beneficial alternative in this regard. Many manufacturers are now investigating the possibilities of the technology to develop airplanes with zero emissions. In the context of hydrogen combustion, the process involves the burning of either liquid or gaseous hydrogen inside a modified gas-turbine engine, resulting in the production of thrust. This process has similarities to the conventional internal combustion process, with the exception that hydrogen has potential to replace the fossil fuel and ultimately reduce emissions. Additionally, hydrogen has several advantages that make it well-suited for the process of combustion. Hydrogen has the ability to undergo combustion when exposed to multiple fuel-air mixtures. Moreover, hydrogen has the capability to operate on a lean combination indicating the quantity of fuel used is lower. As a consequence, there is an increase in fuel efficiency and a decrease in the ultimate combustion temperature, leading to a reduction in the emission of pollutants. Furthermore, the higher auto-ignition temperature of hydrogen enables the utilization of greater compression ratios in a hydrogen-powered engine in comparison to an engine that relies on hydrocarbon fuels. A larger compression ratio leads to increased thermal efficiency, hence reducing energy losses throughout the combustion process.

Nevertheless, the use of hydrogen energy encounters certain technological obstacles that are expected to restrict its potential applications. In particular, the storage of hydrogen requires the use of a strictly controlled environment in terms of temperature and pressure for the hydrogen source, which requires a significant amount of energy. In J. Jensen et al.'s study, several hydrogen sources and storage methods were examined, including compressed and liquid hydrogen [17]. The researchers took into account the energy consumption associated with hydrogen storage, as well as the energy needed to extract the energy from hydrogen sources, in order to determine the overall energy demand for storage.

The energy demand for storage can be assumed as the work required to compress hydrogen in a fixed tank to a certain pressure. The energy consumption associated with compressing hydrogen to various pressure levels was investigated by the researchers. This investigation included adiabatic, ideal, and real isothermal compressions, as seen in Figure 8.

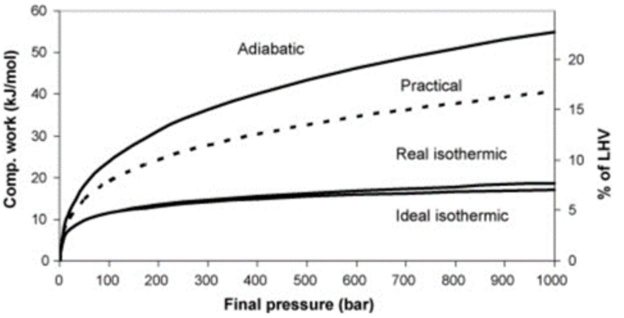

Figure 8. The energy demand for compressing hydrogen to different pressure values [17]

A big benefit of compressed hydrogen is that it can be moved quickly and easily through pipes when the pressure is high enough. Even though the pressure tank cools down as the pressure is let out, the pressure is usually still well above the pressure of the air around it. So, there is no need for energy to release hydrogen. Overall, it is thought that 18% of low heat value (LHV) or 13% of LHV is needed to store the compressed hydrogen at 800 bars. Based on Figure 8, the real situation curve can be estimated, and the energy consumption is about 15.5% of LHV.

One potential theoretical approach for handling liquid hydrogen is the gradual reduction of its temperature from ambient conditions to its boiling point at 20 K, followed by the subsequent condensation of the hydrogen. The mean heat capacity within the specified range is determined to be 28.48 J/mol K, whereas the heat of vaporization at a temperature of 20 K is measured to be 892 J/mol. According to the provided information, the minimum energy needed is determined to be 8.81 kJ/molH2, which corresponds to about 3.7% of LHV. Nevertheless, liquefication contains several other procedures, consequently the process accounts for about 11.8% of LHV. Overall, and depending on the scale of the facility, the realistic energy need for liquefaction is much higher. According to the research, 21% of LHV should be feasible in extremely large liquefaction plants, despite the fact that the energy consumption in today's plant is now in the range of 40–45% of LHV.

4. Conclusion

Turbofan engines are popular in commercial aircraft due to their efficiency in subsonic conditions and fuel efficiency. The previous portion of the study addressed the topic of a turbofan engine equipped with an intercooler. The performance of an intercooled turbofan engine was evaluated. By adjusting the engine characteristics and thermal parameters, such as intermediate compressor pressure ratio (ICP), the fan pressure ratio (FPR), overall pressure ratio (OPR), bypass ratio (BPR), and high-pressure compressor (HPC) pressure ratio, it is possible to achieve a reduction in specific fuel consumption (SFC), resulting in decreased fuel consumption and emissions. Upon engaging in a more extensive examination of the turbofan engine. The discussion revolved around a turbofan engine equipped with an intercooler, which aims to enhance the engine's recuperative capabilities. The findings indicate that the use of the ideal values for bypass ratio, compressor ratio, and heat exchange efficiencies can lead to enhancements of up to 30% in fuel consumption and 20% in engine efficiency. Furthermore, there are other methodologies by which the engine itself may attain the desired objective. This can be accomplished by the combination of several complex thermal cycles and the manipulation of cycle parameters, resulting in better thermal efficiency. It was noted that additional advancements in this area have the potential to enhance efficiency even more. What's more, hydrogen-based energy sources provide considerable promise for future applications, as highlighted in this report. These include hydrogen combustion, as well as the use of hydrogen fuel cells, which was not discussed in this study. Nevertheless, there are other problems that are unavoidable. One example of a topic under discussion is the storage difficulty, alongside another issue related to hydrogen production. The production of hydrogen frequently involves significant energy consumption, with some techniques relying on fossil fuels that produce emissions. This presents a paradox in terms of the intended objective of using hydrogen as a clean energy source. Hence, further study is necessary to address these issues. In conclusion, the primary focus of research in the future of aviation jet engines is in the development of novel engines and power devices that are compatible with low emission fuels, such as hydrogen.

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